Regional Quaternary submarine geomorphology in the Florida Keys

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ABSTRACT

High-quality seismic reflection profiles fill a major gap in geophysical data along the south Florida shelf, allowing updated interpretations of the history of the Quaternary coral reef system. Incorporation of the new and existing data sets provides the basis for detailed color maps of the Pleistocene surface and thickness of overlying Holocene accretions. The maps cover the Florida Keys to a margin-wide upper-slope terrace (30 to 40 m deep) and extend from The Elbow Reef (north Key Largo) to Rebecca Shoal (Gulf of Mexico). The data indicate that Pleistocene bedrock is several meters deeper to the southwest than to the northeast, yet in general, Holocene sediments are ~3 to 4 m thick shelf-wide. The Pleistocene map demonstrates the significance of a westward-dipping bedrock surface to Holocene flooding history and coral reef evolution. Seismic facies show evidence for two possible Holocene stillstands.

Aerial photographs provide information on the seabed surface, much of which is below seismic resolution. The photographs define a prominent, regional nearshore rock ledge that extends ~2.5 km seaward from the keys' shoreline. They show that bands of rock ridges exist along the outer shelf and on the upper-slope terrace. The photographs also reveal four tracts of outlier reefs on the terrace, one more than had been documented seismically. Seismic and photographic data indicate the tracts are >200 km long, nearly four times longer than previously thought. New interpretations provide insights into a youngest possible terrace age (ca. 175 ka?) and the likelihood that precise ages of oxygen isotope substage 5e oöid tidal-bar and coral reef components may differ. The tidal-bar/reef complex forms the Florida Keys.

Keywords: contour maps, coral reefs, Florida Keys, geophysical investigations, outliers, regional sea-level changes.

INTRODUCTION AND BACKGROUND

Detecting evolutionary patterns and processes in coral reef ecosystems is among the main challenges of an integrated Earth system science. The evolution reflects changes triggered by variations in global and regional controls at different scales. Accessibility of the prime fossil record of recurrent Quaternary reef systems in the Florida Keys offers the opportunity to trace these patterns on the south Florida shelf through space and time.

Collaboration with the National Oceanic and Atmospheric Administration (NOAA) has enabled the U.S. Geological Survey (USGS) to conduct geological and geophysical studies on coral reef evolution in NOAA's Florida Keys National Marine Sanctuary (FKNMS; Fig. 1A) over the past 30 yr. High-resolution seismic reflection profiles from a major central area of the keys had been lacking (Fig. 1B). At the time of the profiles' acquisition in 1997, plans were to provide standard geologic data from the survey area as map sets, like those of Lidz et al. (1997a). Growing concern over causes of coral reef decline in Florida, however (e.g., Hallock and Schlager, 1986; Wilkinson, 1993), led to expanded scope and goals. The new objective was to furnish managers and public-policy makers with thorough multifaceted science-based data on regional coral reef evolution in an area of recurrent reef systems. The purpose was to assist in their discerning the difference between natural and human-induced changes and to provide guidance toward design and implementation of procedures having greatest potential for success in reef restoration and conservation. The objective was achieved primarily through use of seismic and aerial photographic evidence supplemented by selected existing core data.

Detecting evolutionary patterns and processes in a specific coral reef ecosystem requires knowledge of underlying bedrock topography and how it developed. Bedrock in south Florida is Pleistocene limestone (e.g., Hoffmeister et al., 1967; Perkins, 1977). Seafloor topography is Pleistocene where bedrock is exposed and Holocene where bedrock is covered by younger reefs or sands. The seismic reflection representing the Pleistocene surface is, for the most part, readily discernible. Thickness or absence of Holocene sediments is also easily determined seismically. Holocene reef thickness is established by coring (e.g., Shinn et al., 1977). In the shallow-shelf setting, high-quality aerial photographs clearly show the seafloor geomorphology, though water depths to pictured features can only be resolved seismically or by diving. Cropped and assembled to create mosaics, the photographs provide invaluable information where seismic data are lacking and especially where geomorphic features are below seismic resolution. The new objective and regional scope of the study required merging the 1997 seismic data with analogous data from reef tract areas surveyed in prior years (Fig. 1B; e.g., Shinn et al., 1990; Shinn et al., 1996; Lidz et al., 1997a). Parameters derived from the seismic, photographic, and limestone core records allow interpretation of regional geologic, hydrologic/oceanographic, and sedimentologic processes. Identifying how processes changed during the Holocene transgression enables interpretation of how various components of the Pleistocene and Holocene reef systems accumulated.

The area surveyed in 1997 extends from just north of Molasses Reef (upper Keys) to Looe Key Reef (lower Keys, Figs. 1A and 1B). The regional area mapped ranges from The Elbow Reef north of Molasses Reef to
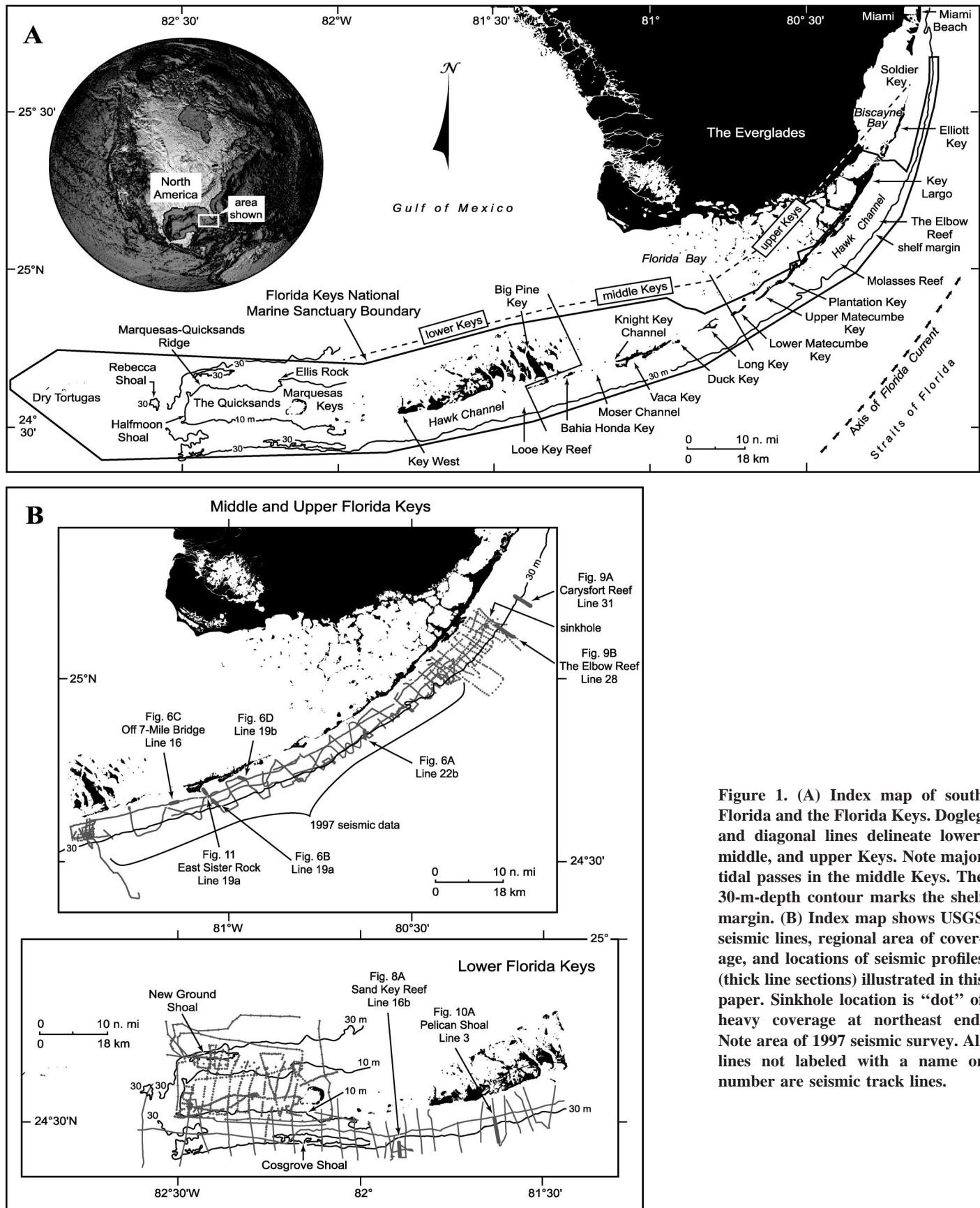
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Figure 1. (A) Index map of south Florida and the Florida Keys. Dogleg and diagonal lines delineate lower, middle, and upper Keys. Note major tidal passes in the middle Keys. The 30-m-depth contour marks the shelf margin. (B) Index map shows USGS seismic lines, regional area of coverage, and locations of seismic profiles (thick line sections) illustrated in this paper. Sinkhole location is "dot" of heavy coverage at northeast end. Note area of 1997 seismic survey. All lines not labeled with a name or number are seismic track lines.
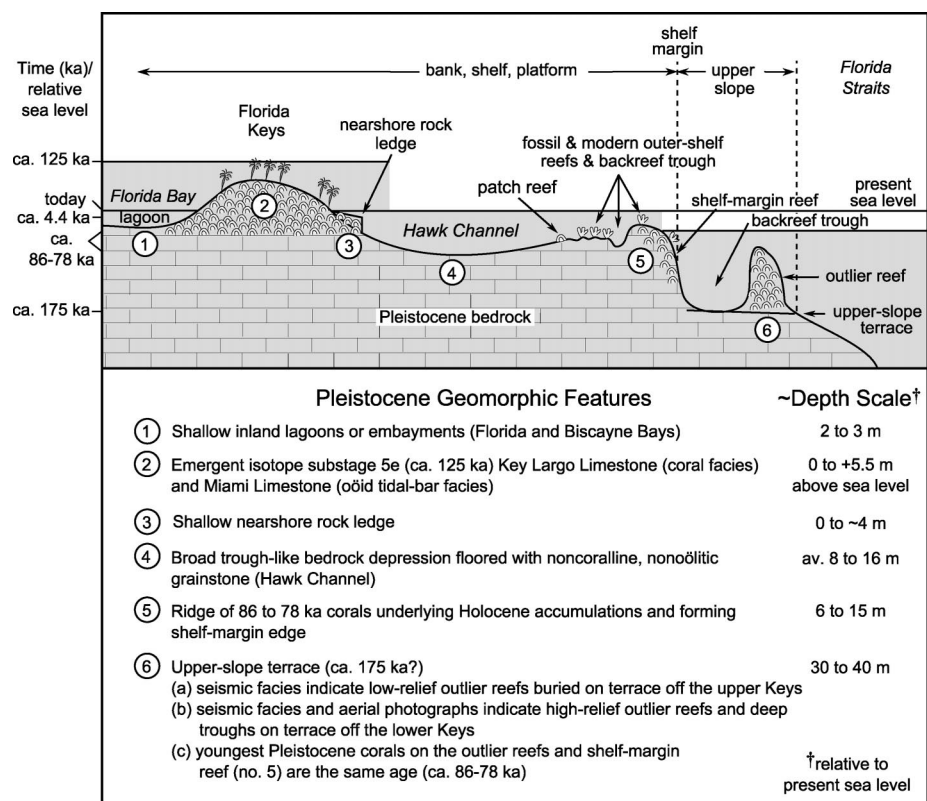
Figure 2. Schematic cross section (not to scale) illustrates six major terrestrial and submarine geomorphic features along the south Florida shelf and terminology used in text.

Rebecca Shoal west of Key West in the Gulf of Mexico and covers ~2130 km², or ~25% of the FKNMS. Aerial photographs led to documentation of a fourth tract of outlier reefs, presented in this paper. Other aspects of the regional study provided indirect evidence for new views on histories of the upper-slope terrace and the oxygen isotope substage 5e reef and tidal bars. This paper also presents the new perspectives.

Generalized Geography and Geology

The south Florida shelf is defined in this study as the submerged part of the platform that extends from the Florida Keys seaward to the base of a Pleistocene coral reef that forms the shelf margin (Fig. 2). The present shelf, as measured between Miami and the Dry Tortugas (Fig. 1A), is 360 km long, 6 to 35 km wide (~5 to 7 km wide of the keys), and generally <12 m deep (Enos, 1977). A broad, sediment-covered upper-slope terrace lies at the toe of the shelf-margin reef in 30 m of water (Lidz et al., 1991; Lidz et al., 1997a). The terrace slopes as much as 2.5 km seaward to a depth of ~40 m and ends where the upper-slope gradient begins to steepen notice-

ably relative to the gradient of the terrace. Except where described otherwise (i.e., Pleistocene surface or Pleistocene bedrock), the term "shelf" refers to the present setting. Because of the shallow environment, all depths given, including depths to bedrock, are relative to present sea level rather than to the seafloor datum normally used in deep-water stratigraphic studies.

The Florida Keys and modern carbonate bank form a curved reef-rimmed margin. The area includes Holocene outer-shelf reefs, the massive shelf-margin reef, and barrier outlier reefs located on the upper-slope terrace. Dates on corals directly beneath Holocene shelf-margin and outlier-reef accretions range from ca. 86.2 to 77.8 ka (Ludwig et al., 1996; Toscano and Lundberg, 1997; Multer et al., 2002). The shelf supports a variety of sedimentary environments and benthic communities (e.g., Jaap, 1984; Dustan, 1985; Shinn et al., 1989).

Curvature of the platform edge produced windward east- and southeast-facing margins and leeward west- and southwest-facing margins (Hine and Mullins, 1983). Direction of prevailing energy (wind and waves) along the southeast margin is from the southeast. In the

Florida Keys, energy direction is both onshore (upper Keys) and tangential to the coastline (lower Keys). West of the keys, strong reversing tidal currents between the Gulf of Mexico and Straits of Florida are important (Shinn et al., 1990). A broad transition in geomorphology occurs along the south-facing margin (Brooks and Holmes, 1989). Unlike other carbonate platforms, this platform has a more fundamental transition between a rimmed margin (east facing; Ginsburg and James, 1974) and a ramp (west facing; Mullins et al., 1988).

The Florida platform is tectonically stable at present (Davis et al., 1992) and exhibits higher elevations to the east (e.g., Parker and Cooke, 1944; Parker et al., 1955; Perkins, 1977). The middle and upper Keys are composed of the oxygen isotope substage 5e (ca. 125 ka) Key Largo Limestone coral reef. The lower Keys consist of the Miami Limestone oölite of the same age. The formations developed when sea level in Florida was ~10.6 m higher than today (e.g., Sanford, 1909; Hoffmeister and Multer, 1968; Perkins, 1977). Cross-bedded Miami Limestone oölite also underlies the city of Miami. Bedding in the Miami unit dips east and west (Halley and Evans, 1983) and south with progradation of the barrier-bar facies (Grasmueck and Weger, 2002). Bedding in the lower Keys unit dips north and south (Kindinger, 1986). Seaward of the keys, the limestone bedrock in Hawk Channel (Figs. 3A and 3B) is bioturbated grainstone (Shinn et al., 1994). The bedrock surface of the shelf is unusually flat and smooth when compared with the reefs, sand shoals, patch reefs, rubble, and mud banks that comprise the irregular Holocene surface (Enos, 1977). Enos noted that erosion during the Holocene transgression may have smoothed the bedrock somewhat, but he regarded most of the shallow closed depressions as karst formed by groundwater dissolution, rather than by stream or wave erosion or by depositional topography. Karst features are typical in carbonate environments (e.g., Wilson, 1975; James and Choquette, 1988; Ford and Williams, 1992; Halley et al., 1997; Kindinger et al., 1999).

METHODS

Geophysical Data Acquisition and Processing

High-resolution seismic reflection profiles provide the data for interpreting depth of the Pleistocene bedrock surface and thickness of Holocene sediments. Equipment for the 1997

survey included proprietary seismic software (Delph Seismic manufactured by Elics) with a 32-bit digital signal processor running on a portable PC and Windows 95 operating system. Hard-copy profile data were generated on a gray-scale thermal plotter that automatically recorded track-line shotpoints and latitude and longitude from a GPS (Global Positioning System) receiver on the profiles at 1 min intervals. A precision lightweight GPS receiver using encryption recorded GPS navigation data. A laptop running real-time GPS mapping software and Windows 95 collected and displayed navigation data in real time. The seismic system triggered an ORE Geopulse power supply towed on a catamaran sled. The return signal was bandpassed, allowing only signals between 400 and 4000 Hz to pass. The power supply produced underwater acoustical pulses at either 60 or 135 J depending upon sea state and substrate. Shot intervals ranged from 250 to 350 ms. A 10-element hydrophone received the reflected acoustical pulses and fed them directly into the seismic system for storage and processing.

Bedrock-surface and sediment-isopach data, read from the seismic records at 5 min intervals, provided distances (depths) from the sea surface to bedrock and sediment surfaces in two-way traveltime measured in milliseconds. Significant changes in depth to bedrock or sediment thickness between the 5 min intervals required shorter-interval readings. The measured difference between the depth from sea level to the seafloor surface and the depth to the reflection identified as Pleistocene bedrock produced data in milliseconds for the sediment isopach. Seafloor-surface depth, bedrock depth, and isopach in milliseconds were converted to depths in meters in an Excel spreadsheet; the conversion compensated for a 7 m sound source/receiver offset. All interpreted depth measurements including thickness of seafloor sediments were based on the average velocity (assumed) of sound in shallow seawater (1500 m/s). The seismic data were not calibrated to core/probe thickness to determine actual velocity of the sediments. More specific evaluations for different sediment velocities in the more mud-bearing northern sediments vs. the sand-dominated lower Keys sediments can be found in Incze (1998). The geophysical data used to construct the contour maps (Figs. 4A and 4B)[1] represent different vintages of data collected over the

years with two 50-ft-long (15 m) vessels. Reef thickness in many locations on the shelf was determined from earlier coring (e.g., Shinn et al., 1977, 1994; Shinn, 1980; Lidz et al., 1985).

Depth to bedrock and reef/sediment thickness were plotted by computer at appropriate GPS points on track-line navigation maps at a scale of ~1:24,000. Plotted data were intentionally contoured by hand aided by aerial photographs that provided visual cues for geomorphic trends. A commercial GIS (geographic information system) computer software package generated seismic track-line navigation maps. Data stored in Excel included GPS shotpoint coordinate fixes and annotations, track-line names, and depths to interpreted horizons. A default map scale set by the software allowed data plotting relative to shotpoint location. Depth to interpreted horizon was plotted next to each shotpoint annotation. A Florida Keys shoreline outline was added to the maps by using the National Ocean Service Digital Shoreline Data set. Track-line labels, geographic coordinate grid, and a scale bar were superimposed on each map. A GIS translation plug-in allowed importation of digital files of the maps into a computer drawing program for page-layout manipulation.

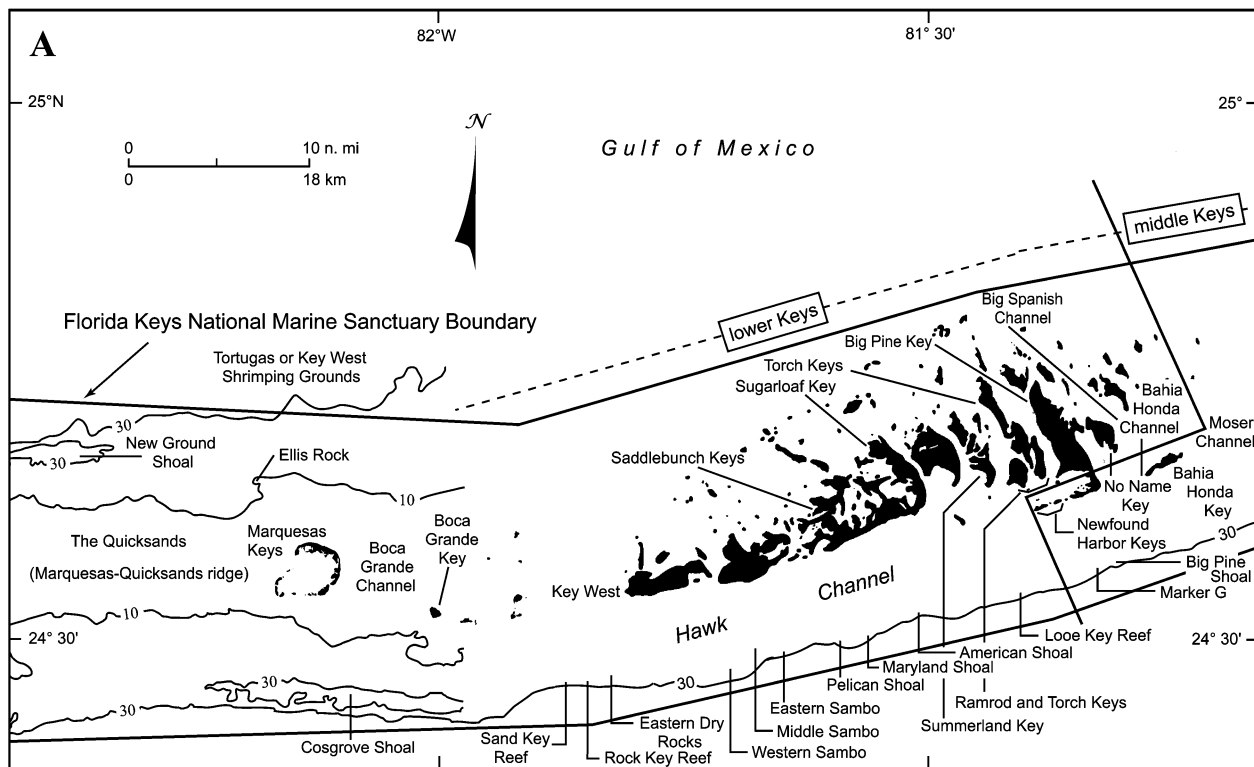[1]Figures 4A and 4B are on a separate sheet accompanying this issue.

Figure 3. (Above and on facing page.) Contiguous index map shows locations of named reefs and shoals in (A) the lower Keys and westernmost part of the middle Keys, and (B) the middle and upper Keys. Contours in meters.
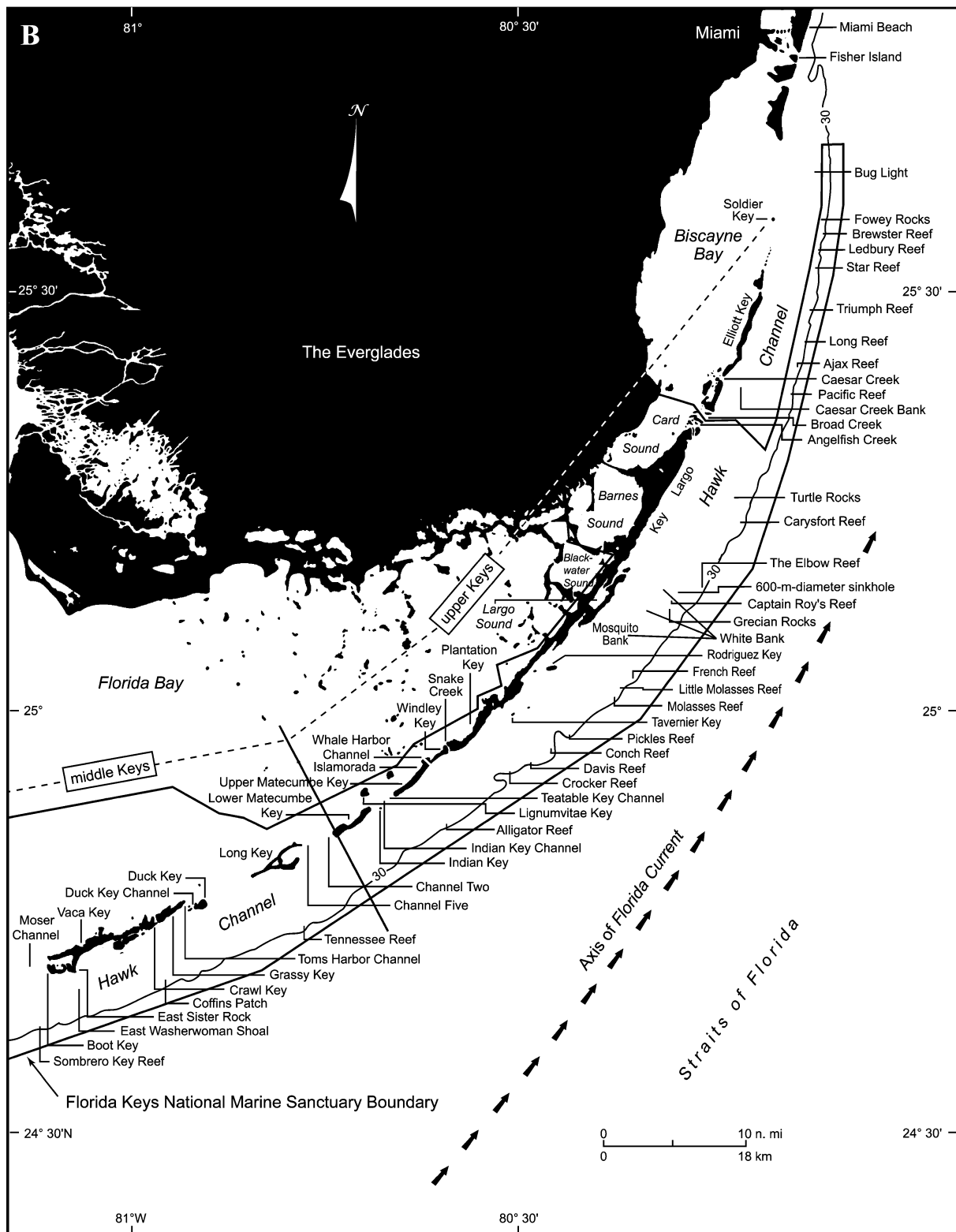
Figure 3. (*Continued.*)

Geophysical Data Integration

Integration of the contoured 1997 seismic data from >300 line kilometers of profiles with completed maps contoured from analogous USGS data collected earlier resulted in revision of parts of the published maps that overlapped with the 1997 data. The published maps were limited in extent, having focused on specific inner- and outer-shelf areas within the FKNMS (refer to Figs. 1A, 1B, 3A, 3B): (1) upper Keys, ~100 km of shelf profiles obtained in 1991 between The Elbow Reef and Molasses Reef (Lidz et al., 1997a; Lidz et al., 1997b); (2) lower Keys, ~114 km of profiles acquired in 1983 within and adjacent to the Looe Key National Marine Sanctuary at Looe Key Reef (Lidz et al., 1985); (3) lower Keys, ~500 km of profiles obtained in 1989 offshore between Summerland Key and Boca Grande Key (Lidz et al., 1991, 1997b); and (4) west of the lower Keys, ~640 km of profiles acquired in 1981, 1983, and 1989 from Boca Grande Key and the Marquesas Keys to the west edge of the Marquesas-Quicksands ridge, including Ellis Rock, and New Ground, Rebecca, Halfmoon, and Cosgrove Shoals (Shinn et al., 1990). The five integrated data sets represent ~1655 line kilometers of seismic data that allowed a comprehensive updated compilation of regional records of bedrock topography and Holocene thickness.

Isolated data on bedrock depth below sea level, interpolated from maps of Enos (1977, scale 1:80,645), supplemented the merged bedrock data set. Enos was the first to map bedrock topography and sediment thickness along the shelf from Fowey Rocks (Fig. 3B) to Key West with geophysical methods (a subbottom-sparker profiling system available at the time). GPS did not exist in the late 1960s when Enos acquired his data. Traverse positions thus depended on direct line of sight between two fixed objects, such as a navigational marker and specific points on land, although the 20-ft-long (6 m) boat used probably drifted sideways with the current and circumvented lobster-trap floats and near-surface head corals, as was necessary during our studies. Thus, not all of Enos's bedrock data correlated with those obtained by using GPS. Because his data were not digitized, Enos's track lines were superimposed by hand on separate overlays by using a protractor and ruler. Although somewhat generalized, some of his bedrock data nonetheless corresponded well with our 1997 data. Track lines off the upper Keys provided the best and most correlative data. Parts of lines off the middle Keys plotted off those on our maps by as

much as 1 km, limiting use of those data. Track lines off the lower Keys where currents are strongest plotted several kilometers off and could not be used.

To interpolate Enos's data and transfer them to the new maps, the distance along each 1977 track line where the line was intersected by a contour of the merged USGS data was measured with two-point dividers and adapted to the scale of the new maps. Enos's data, in U.S. units, were converted to meters and plotted on the overlays. The new contours were adjusted slightly where his bedrock data could be used and were digitized. Because the contours were not in any projection, an empty template coverage was created, and the coordinates were transferred from Degrees Minutes Seconds to Decimal Degrees. A minimum of four tics (control points) was used in each map. Most maps have six tics. The contours were then projected into a Universal Transverse Mercator projection for digitizing as map units (meters) and attributed to produce the Pleistocene topography and Holocene isopach maps.

RESULTS

A Nearshore Rock Ledge

Aerial photographs show that a nearshore rock ledge borders the seaward side of the Florida Keys and forms a major regional shallow (0 to ~4 m) seabed structure (e.g., Figs. 5A and 5B). The ledge has not been mentioned in the literature other than by passing reference to its seaward scarp that marks the boundary between nearshore hardbottom communities and biota that inhabit the muddy grass-covered environment of Hawk Channel (Marszalek, 1977). Although presence of the ledge is an interesting and potentially significant finding, evidence is currently insufficient to derive solid conclusions about its history or to evaluate its implications. The paucity of data on such a potentially significant finding unfortunately puts discussion of what is known about the ledge beyond the scope of this paper. We mention its presence, however, because the ledge is clearly visible in several of the photographs used in this paper to illustrate other geomorphic trends discernible in the seabed floor.

Pleistocene Topography

The Pleistocene surface map shows that bedrock elevation varies locally but dips regionally several meters westward (Fig. 4A). On average, shelf bedrock ranges from ~8 to 12 m below sea level off the upper Keys but

is typically 10 to 16 m deep off the lower Keys, a distance of ~240 km. Average bedrock depth in Hawk Channel ranges from ~8 to 12 m off Key Largo, from ~12 to 18 m off the lower Keys, and from ~18 to 24 m off the Marquesas-Quicksands ridge west of the lower Keys. Depths south of the ridge represent the westward extension of the depression under Hawk Channel. The broad (~28 by 47 km) flat ridge is the submerged extension of the Pleistocene surface that forms the lower Keys (Shinn et al., 1990). The bedrock surface on the ridge has numerous isolated depressions and solution holes and is usually capped by calcrete. Bedrock ranges from 0 to 12 m below sea level but is typically ~6 to 8 m deep along the ridge. Bedrock around the ridge is 20 m or more deep except in Boca Grande Channel (Fig. 3A). Currents in Boca Grande Channel flow through a shallow (~6 to 8 m), sediment-free, north-trending depression in the arcuate promontory formed by the Florida Keys and Marquesas-Quicksands ridge. The bedrock-surface map also shows that trends of geomorphic features seaward of the keys generally parallel the curved shelf margin. The prime example is the bedrock low beneath Hawk Channel.

In the vicinity of the keys, sinuous intra-island tidal channels generally track southward as they exit Florida Bay (Figs. 5A and 5B). Interpretation of whether an ancillary depression (i.e., vs. Hawk Channel) seaward of the keys represents a channel, riverbed or karst is not possible because of incomplete seismic definition of the feature. However, seismic data point to a possible connection from tidal channels in the middle Keys across the bedrock depression under Hawk Channel to a topographic low at the shelf margin. Tennessee Reef (Fig. 3B) occupies a bedrock high (8 to 10 m below sea level, Fig. 4A) south and southwest of channels at either side of Lower Matecumbe Key through which a forked bedrock depression, thought to represent a Pleistocene riverbed (Davies, 1980), exited Florida Bay.

Individual bedrock lows on the shelf were not seismically defined. Their seismic shapes and widths are thus either true (seismic line is perpendicular to the trend of the depression) or apparent (seismic line is tangential to the trend). Except where a track line crossed normal to the shelf margin, most seismic shapes are probably apparent. Bedrock depressions are clearly discernible, and most are filled with Holocene sediment (Figs. 6A–6D). When mapped following the general margin-parallel geomorphic trend in the region, the depressions range from elongate closed features, to
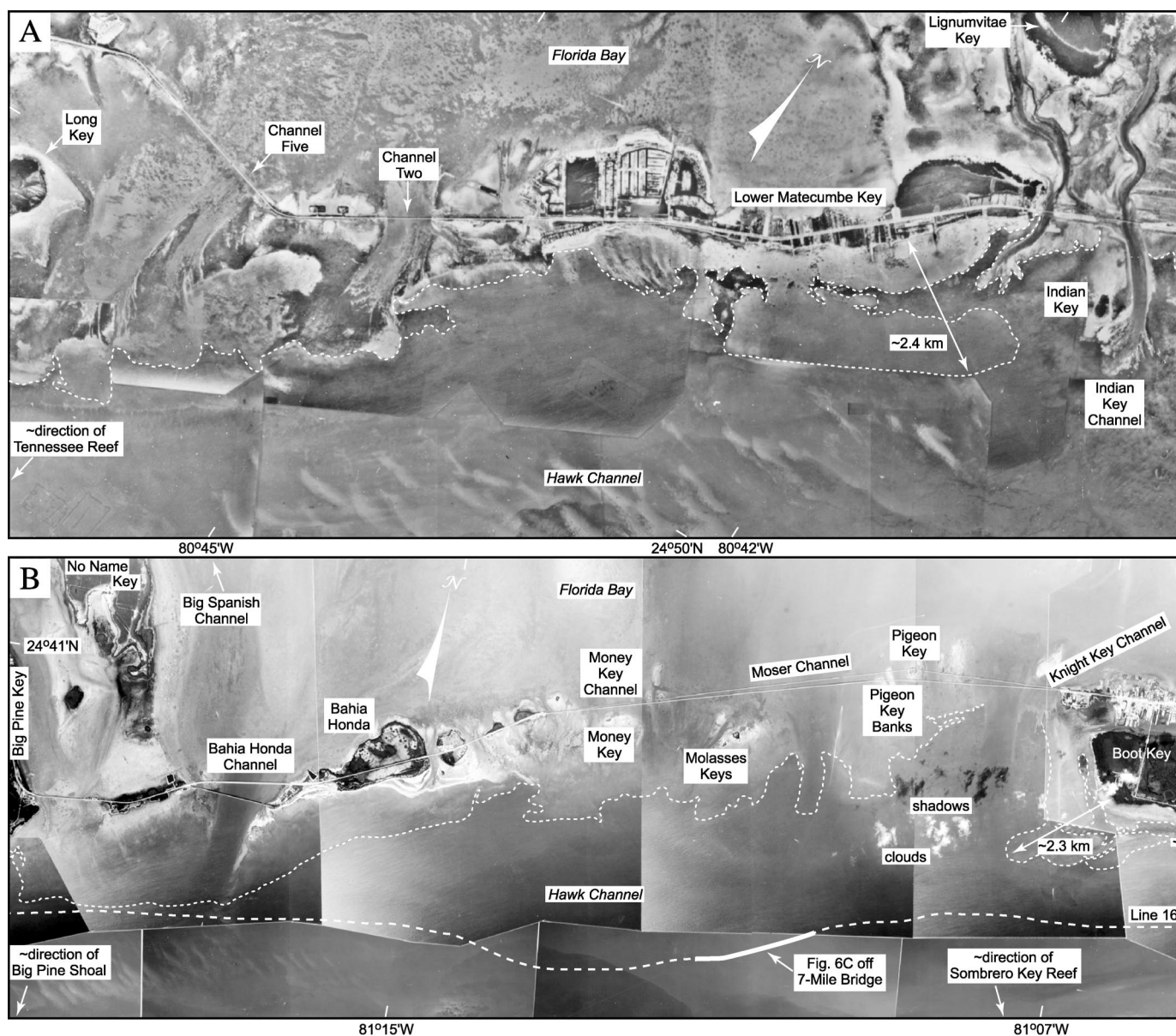
Figure 5. Photographs taken in 1991 show sinuous intra-island tidal channels in areas of (A) Lower Matecumbe Key (middle Keys), and (B) Moser Channel (lower middle Keys; see Figs. 1A, 3A, and 3B for locations; Money Key, Molasses Keys, and Pigeon Key are represented by dots in Moser Channel in Fig. 1A). White dotted line marks seaward edge of nearshore rock ledge. Note tidal-delta sediments within channels or at channel edges. Compare solid area of seismic line 16 in B with surface and subsurface features in Figure 6C.

local narrow sinuous conduits, to broadly defined areas.

With one exception, Bahia Honda Channel, water depth to bedrock within tidal passes between the keys is inferred. Despite great width, in some cases many kilometers, the passes are too shallow to accommodate the vessels required to navigate rough seas on the outer shelf and shelf margin. The widest passes are in the middle Keys, but the widest pass is not the deepest. Field observations and navigational charts indicate that bedrock in most

channels is ~4.5 m deep at most. The deepest pass anywhere in the keys may be the depression under Bahia Honda Channel, located south of the eastern lower Keys (Figs. 3A, 5B). Records maintained by Overseas Railway engineers in the early 1900s noted that bedrock encountered during bridge construction was deepest in Bahia Honda Channel (Spanish for "Deep Bay;" Parks, 1968). Railway workers recorded maximum depth at 10.7 m below sea level, but they "hit a spot that was not only deep but seemed bottomless. It took a

shipload of sand, gravel, and cement to fill" (Parks, 1968, p. 23). Neither our seismic data nor those of Enos (1977, his Fig. 39F) provide adequate coverage to confirm the 10.7 m depth or to connect this channel to the shelf margin. Aerial photographs also provide no evidence of a connection. However, both seismic data sets indicate a deep area (>13 m below sea level, Fig. 4A) just south of the channel, and Bahia Honda Channel may be the southern extension of Big Spanish Channel (Fig. 3A). Navigation charts show that
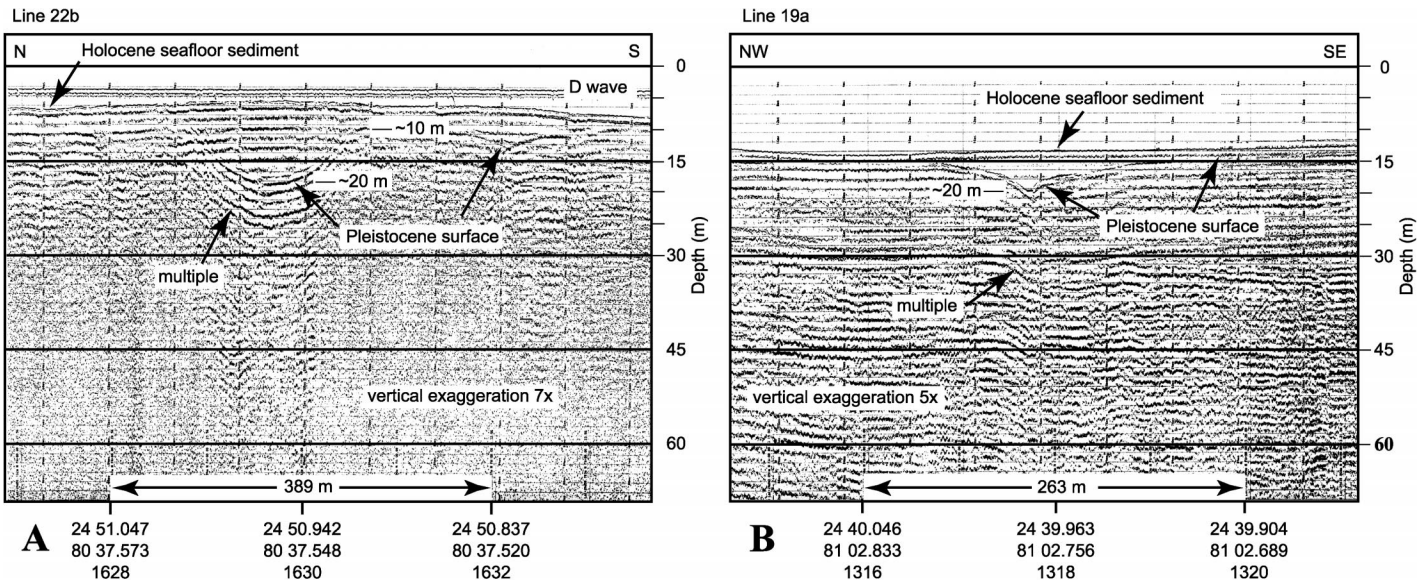
Figure 6. Seismic profiles acquired in 1997 show Pleistocene surface features and overlying Holocene sands (see Fig. 1B for profile locations). Difference between bell-shaped or V-shaped bedrock depression can be the angle at which the seismic line intersects the depression. Oblique angle will make a depression look broader; a crossing normal to the same depression will make it look V-shaped. (A) Bell-shaped depression, possibly its true shape, located just northwest of Alligator Reef (upper Keys, Figs. 1B, 3B). D wave = direct arrival. (B) V-shaped depression just east of East Washerwoman Shoal (middle Keys, Fig. 3B) may also be a true shape with a southeastward trend (Fig. 4A).

seafloor depths within Big Spanish Channel are ~2 to 4 m (National Oceanic and Atmospheric Administration, 1993). The combined channels connect the Gulf of Mexico with Hawk Channel today (Smith, 1994).

Bedrock depth in the widest tidal pass in the middle Keys, Moser Channel (14.5 km wide, Figs. 1A, 1B, 5B, 6C, and 6D), is also inferred from field observations to be no more than ~4.5 m below sea level at most. Passes between islands in the middle Keys are thought to represent natural divides between reefs in the uppermost part of the Key Largo Limestone. Where not covered by sediment or mangroves, the Key Largo reef is usually visible. During Pleistocene lowstands, the divides were likely areas where rainwater runoff from higher inland elevations drained toward the shelf edge. The channels are thus probably subaerially eroded in part. In the lower Keys, Pleistocene tidal currents cut narrow channels in loose oöids at the time of their deposition, forming marine tidal bars and swales prior to subaerial induration (Hoffmeister et al., 1967). Because the oölitic tidal bars overlie the Key Largo reef, the lower Keys passes are presumably shallower than those in the Key Largo Limestone.

Water depth to the crest of the shelf-margin reef varies from ~5 to 8 m (upper Keys) and from ~7 to 15 m (lower Keys). The deepest bedrock areas at the margin and on the outer shelf are in the middle and lower Keys. Like the bedrock surface on the shelf, they become progressively deeper from northeast to southwest (Fig. 4A). Water depths to bedrock around Alligator (6 to 12 m, Fig. 7A), Tennessee (10 to 14 m, Fig. 7B), Sombrero (12 to 16 m), Looe Key (12 to 18 m), and Sand Key Reefs (14 to 18 m, Figs. 8A and 8B) are likely related to the westward-dipping trend of the shelf.

Bedrock bounding the north, south, and west sides of the Marquesas-Quicksands ridge is 20 m and more below sea level. The area north of the ridge generally defines the southeast boundary of a region known locally as the Tortugas or Key West Shrimping Grounds (Fig. 3A). The area south of the ridge is located 8 to 10 km north of the shelf margin and upper-slope terrace bordering the Straits of Florida. The west end of the ridge drops abruptly into an unnamed north-trending channel between the ridge and Rebecca Shoal (Fig. 4A). The east end is bounded by current-swept Boca Grande Channel. Although water depth to bedrock in Boca Grande Channel is similar (~6 to 8 m) to that on the ridge, a higher elevation and the Marquesas Keys at the east end of the ridge isolate the ridge from the channel. The higher-elevation area is forked and forms two narrow, parallel ridges that lie 0 to 2 m below the sea surface. Clearly evident on bedrock and isopach maps (Figs.

4A and 4B), the narrow ridges border a shallow ovoid depression in which Holocene mud has accumulated. Mud thickness (~4 m) was determined by probing to bedrock with a rod (Shinn et al., 1990). The Marquesas Keys, composed of Holocene *Halimeda* sands (Hudson, 1985), surround the depression. Deep water on three sides of the ridge and sediment-free Boca Grande Channel indicate that sediments on the ridge are formed in place (Shinn et al., 1990).

Upper-Slope Geomorphic Features

The 1997 seismic data confirm what analogous published data off the upper and lower Keys had indicated—that the upper-slope terrace is regional. Though variable in width, the terrace surface underlying Holocene sediments occurs at roughly the same water depths margin-wide. Its landward edge is at the 30-m-deep toe of the Pleistocene shelf-margin reef. The terrace slopes seaward to a depth of ~40 m over a distance of as much as 2.5 km. The narrowest parts coincide with margin re-entrants and with the deepest areas along the shelf at Alligator, Tennessee, Looe Key, and Sand Key Reefs and at Big Pine Shoal (Figs. 3A, 3B, and 4A). Aerial photographs show that outlier reefs are absent in these areas and that the terrace is generally a flat featureless sand-covered terrain that blends in with the
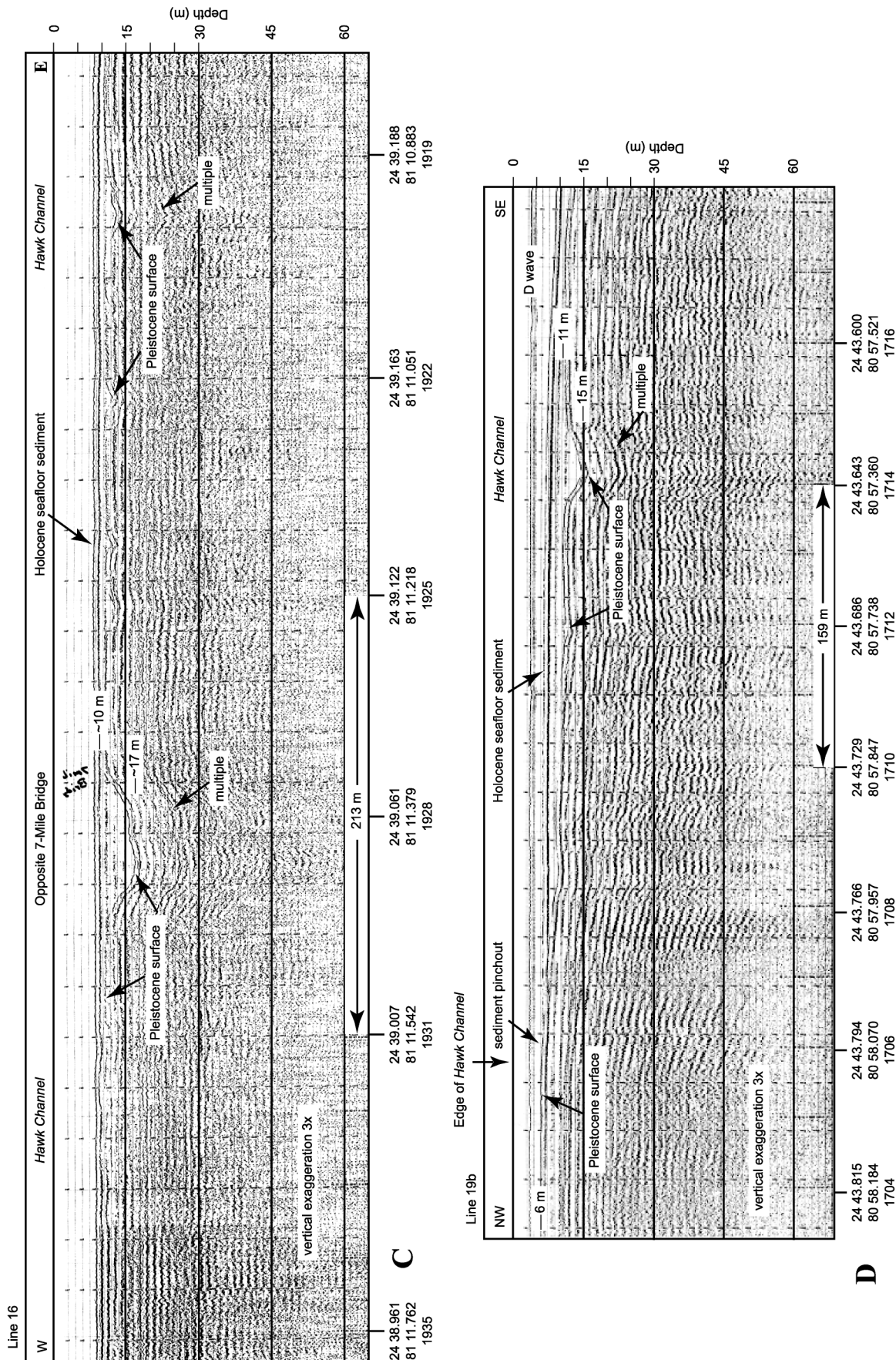
Figure 6. (*Continued.*) (C) Large depression in main bedrock low along north edge of Hawk Channel. Seismic line is ~4.6 km south of and opposite Seven Mile Bridge crossing Moser Channel. Bedrock beneath the bridge is ~4.5 m below sea level. Correlation of seismic profile (C) with photograph (Fig. 5B) and a navigational chart (National Oceanic and Atmospheric Administration, 1993) indicates that the large seismic depression may be a deeper extension of the depression under Moser Channel. No seismic evidence of Knight Key Channel was visible on the eastern part of the profile (not shown). (D) Bedrock depression (at right) southwest of Toms Harbor and Duck Key Channels (middle Keys, Fig. 3B) may represent one of those two channels. Note sediment pinchout (at left) against smooth bare grainstone surface under Hawk Channel (Shinn et al., 1994). D wave = direct signal. Latitude and longitude in decimal minutes are based on GPS coordinates. Hours (military time) adjacent to ticks are navigational correlation points along seismic lines.
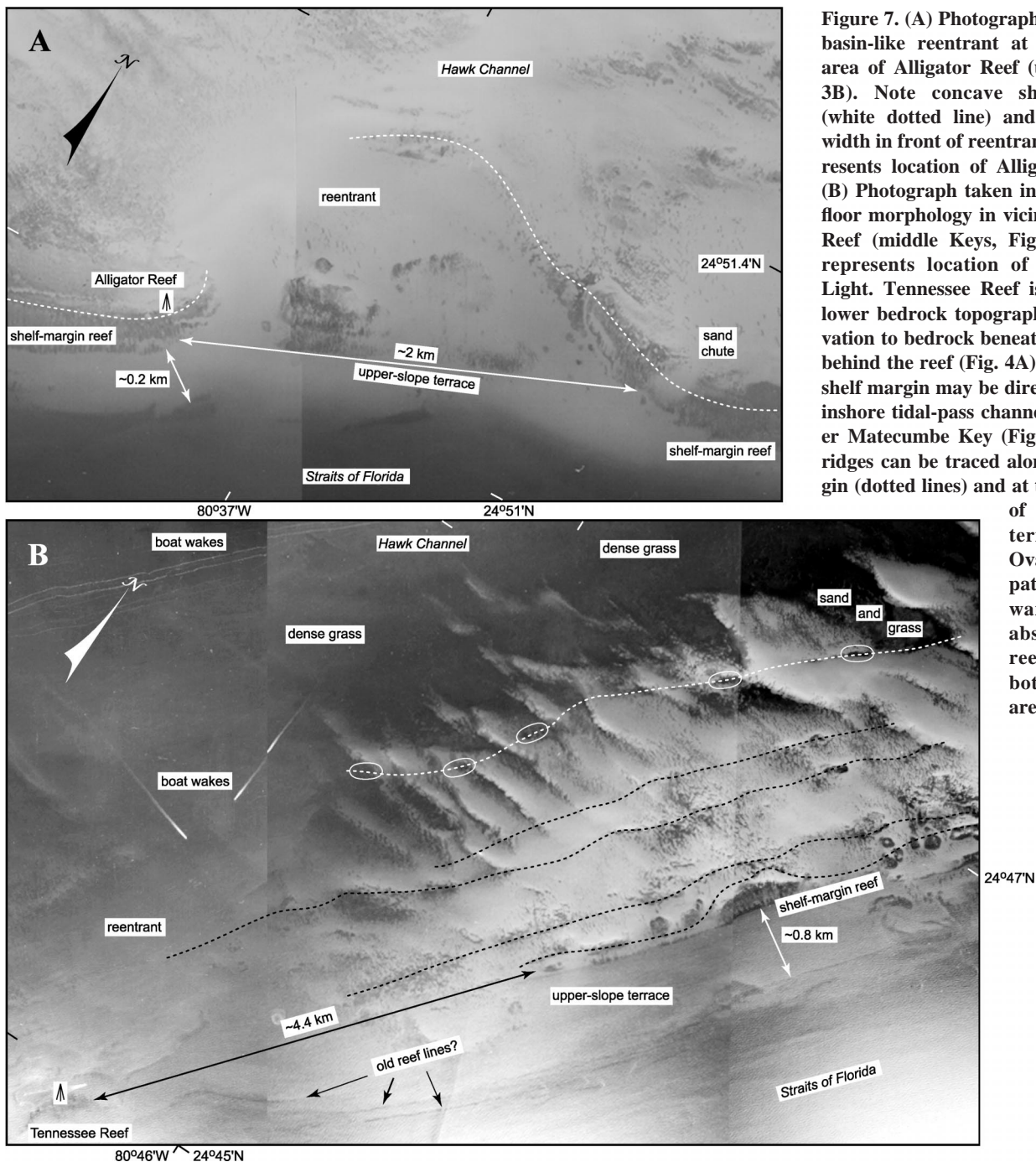
Figure 7. (A) Photograph taken in 1991 of basin-like reentrant at shelf margin in area of Alligator Reef (upper Keys, Fig. 3B). Note concave shelf-margin reef (white dotted line) and narrow terrace width in front of reentrant. "Tripod" represents location of Alligator Reef Light. (B) Photograph taken in 1975 shows sea-floor morphology in vicinity of Tennessee Reef (middle Keys, Fig. 3B). "Tripod" represents location of Tennessee Reef Light. Tennessee Reef is surrounded by lower bedrock topography similar in elevation to bedrock beneath Hawk Channel behind the reef (Fig. 4A). This area of the shelf margin may be directly connected to inshore tidal-pass channels south of Lower Matecumbe Key (Figs. 3B, 5A). Rock ridges can be traced along the shelf margin (dotted lines) and at the seaward edge of the upper-slope terrace (arrows). Ovals mark areas of patch reefs on landward ridge. Note absence of outlier reefs seaward of both reentrant areas.

reentrants (e.g., Figs. 7A and 7B). In many places, bands of linear rock ridges paralleling the shelf margin can be traced through sands in the photographs. Some of the ridges line the outer shelf; others mark the seaward edge of the terrace (Fig. 7B). Cores transecting two outer-shelf ridges in the lower Keys show they consist of massive Pleistocene and Holocene corals separated by a sediment-filled swale (Shinn et al., 1977). South of the Marquesas-Quicksands ridge, the terrace is for the most

part very narrow until it broadens to >3 km wide southwest of Halfmoon Shoal and south of Rebecca Shoal. A wide 30-m-deep terrace on the west side of Tortugas Bank ~18 km west of the Dry Tortugas (Mallinson et al., 2003) may mark its westernmost extent.

Lidz et al. (1991) were the first to describe and document seismically three linear tracts of outlier reefs on the lower Keys terrace (Fig. 8A). Those authors described the reefs as being ~57 km long. In this paper, we photo-

graphically document four distinct tracts in the same area (Fig. 8B). Regional photographic and seismic data indicate that one or more discontinuous tracts parallel the margin from Alligator Reef to south of Rebecca Shoal, a distance of ~213 km. Their varied relief and discontinuity and the navigational constraints imposed by strong offshore currents prevent consistent recording of an individual tract over the 213 km. The four tracts exist more or less together between Coffins Patch and Boca
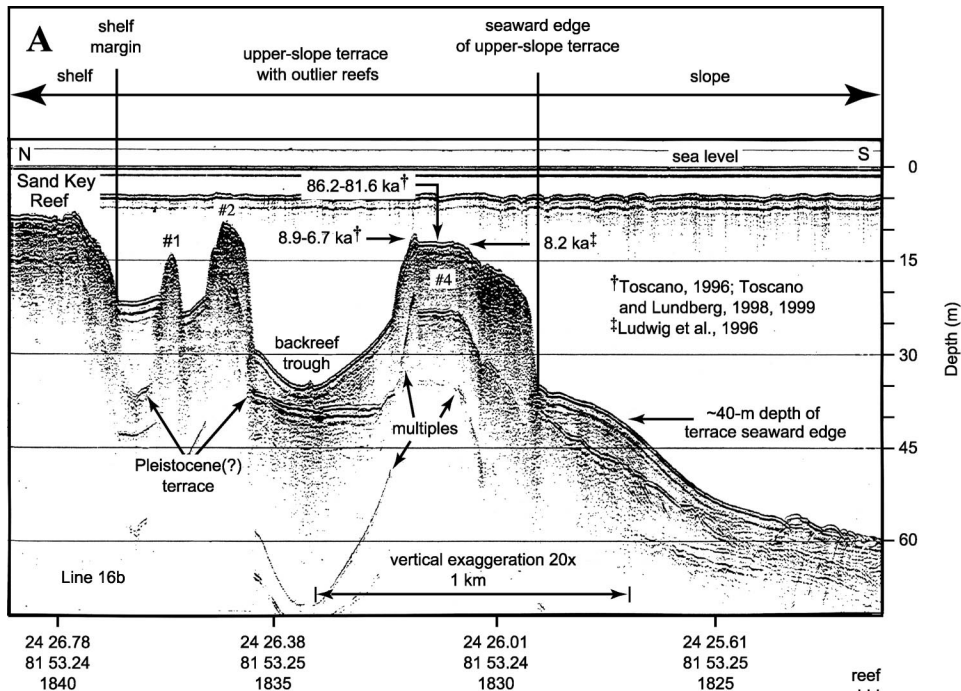
Figure 8. (A) Original seismic data documenting three tracts of outlier reefs off Sand Key Reef southwest of Key West (Fig. 3A). Numbered reefs correspond to numbered tracts in B. Largest outlier, cored and dated, developed at seaward edge of broad upper-slope terrace. Note discontinuity of Holocene section on reef crest. Also note reflection representing gently sloping, nearly flat terrace surface between outliers and lack of reflections beneath the reefs. Coral reefs and reef rubble typically obscure sound-wave reflectivity of underlying rock surfaces. Latitude and longitude in decimal minutes based on GPS coordinates. Hours (military time) adjacent to ticks are navigational correlation points along seismic line.
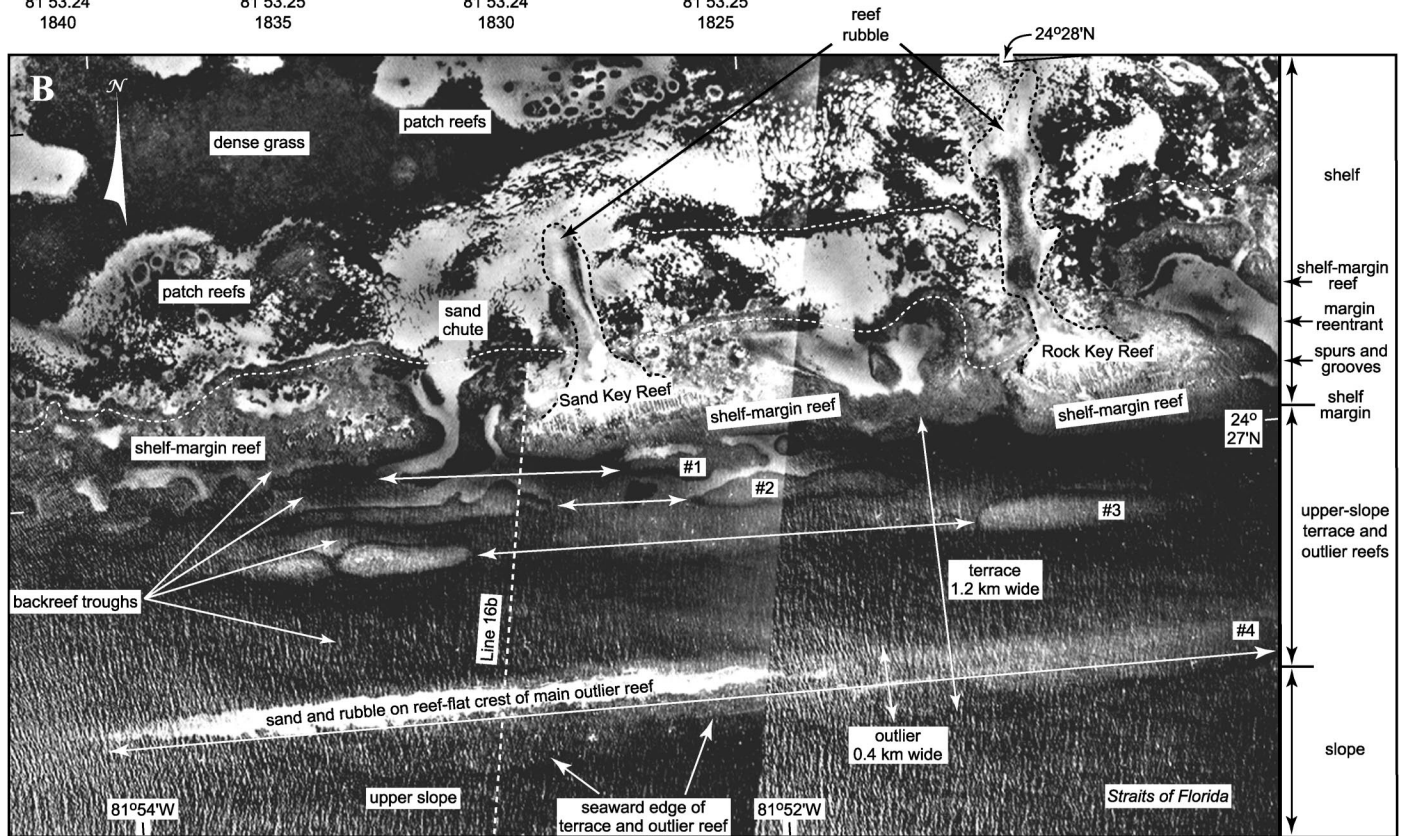
(B) Photograph of Sand Key Reef area taken in 1975 shows four tracts of outlier reefs (nos. 1–4) and their sandy backreef troughs. Seismic line in A just missed tract 3. Note discontinuity of Pleistocene shelf-margin reef and discontinuity and hummocky outlines of outliers. Also note landward patch reefs, linear Holocene spurs and grooves at seaward edge of Sand Key and Rock Key Reefs, and ovate zones of storm-transported reef rubble behind the two reefs. White dotted lines mark outer-shelf rock ridges. Compare with geomorphic features in areas of major margin reentrants (Figs. 7A and 7B).

Grande Key (Figs. 3A and 3B). Two continue to the northeast and terminate just west of Alligator Reef. A single oval-shaped outlier is located off Conch Reef in the upper Keys, and a single tract extends westward to the west edge of the Marquesas-Quicksands ridge. Northeast of Conch and The Elbow Reefs in the vicinity of Carysfort Reef (Figs. 3B, 9A, and 9B), what may once have been an outlier reef (on a shallower, more landward terrace?) now underlies Holocene reefs and sediments.

Seismic reflections off Pelican Shoal indicate several other types of structural and stratified features at the lower Keys shelf margin (Figs. 3A, 10A, and 10B). (1) An infilled (with ~16 m of Holocene sediments and reefs) V-shaped trough exists behind the Pleistocene shelf-margin reef. (2) The surface of the upper-slope terrace is wide, flat, and nearly horizontal. (3) A concave, possibly wave-cut surface is present in the base of the shelf margin. (4) At a water depth of ~25 m, a sharp stratigraphic contact is present between inclined and flat bedding in a Holocene sediment wedge on the terrace. (5) A poorly developed reef or possible beach-dune ridge caps the seaward edge of the terrace in ~30 m of water.

Holocene Accumulations

Holocene seismic data are biased toward sediment and deeper reef areas because the vessels circumvented shallow reefs and sand shoals and because reefs tend to obscure seismic signals. The most notable observation derived from the regional isopach map is that, despite lower bedrock elevations to the southwest, Holocene sediments are generally ~3 to 4 m thick over most of the shelf, including on the upper-slope terrace (Fig. 4B). Sediments are thinnest on average on the Marquesas-Quicksands ridge and along the inner shelf where they pinch out at the edge of the Hawk Channel depression (Fig. 6D). Sediments are absent on the seaward face of the shelf-margin reef but are >20 m thick in the trough behind the reef (Fig. 9B). Along areas of the outer shelf where most Holocene coral reefs developed, thickness of Holocene accretions ranges from 12 (lower Keys) to 18 m (upper Keys) with an average range of 7 to 8 m shelf-wide. A 600-m-diameter sinkhole located off north Key Largo (Figs. 1B, 3B) probably contains the thickest (>55 m) sediments on the shelf (Shinn et al., 1996).

Accreting offshore sediments include fine-grained muds and coarse-grained sands that for the most part remain where they are produced (Ball et al., 1967). Lime mud and mud-dy sand cover the floor of Hawk Channel. Localized areas of clean carbonate sand such as at White Bank off the upper Keys (Fig. 3B) are found seaward of Hawk Channel. Porous reef framework, coral rubble, and sand covered by sparse to dense beds of turtle grass (*Thalassia testudinum*) are typical in patch-reef environments and in areas behind outer-shelf rock ridges (e.g., Fig. 8B). Oblong sand-and-rubble washovers are common behind Holocene shelf-margin reefs where storms have transported reef debris landward (e.g., at Sand Key and Rock Key Reefs; Fig. 8B). Grass-free sands blanket the upper-slope terrace (Figs. 7A and 7B).

Antecedent topographic highs, most of which were Pleistocene reefs, localized most Holocene reefs (Shinn et al., 1989). Holocene reefs also colonized cemented sand dunes (Shinn et al., 1977). For unknown reasons, however, not all bedrock highs were colonized (Fig. 11). The shelf flooded in a northeastward direction owing to westward slope. Coral growth, confirmed by ^{14}C dates, thus began earlier off the lower than upper Keys (e.g., Shinn et al., 1977). Reefs lived longer off the upper Keys, however, because offshore islands that are now submerged protected them from high-energy waves (e.g., Shinn et al., 1989). High- or low-energy conditions were important to early Holocene coral recruitment and to the type of species that would colonize a reef. Coring has shown that many reefs consist of zones of different coral species and that reefs have backstepped over coral rubble or carbonate sand as water depth and wave energy changed with rising sea level (e.g., Figs. 12A and 12B; Shinn, 1980; Lidz et al., 1985). Coral zonation is dependent on geographic location, proximity to tidal passes, incursions of cold and/or turbid and nutrient-rich water, maturity of reef profile, and sediment production (Jaap, 1984). Today, turbid variable-salinity bay waters and cold Gulf of Mexico waters affect reef survival. The unbroken island of Key Largo protects the reefs off the upper Keys from their impact (Ginsburg and Shinn, 1964).

DISCUSSION

The primary influences on recurrent development and distribution of the Florida Keys coral reef systems were paleotopography and a fluctuating sea level. In Florida, regional controls at different scales also played a role, particularly prevailing southeasterly winds and waves impinging on a curved, westward-sloping shelf margin. Pleistocene reefs consisted primarily of massive head corals and lacked *Acropora palmata* (e.g., Hoffmeister, 1974). During the Holocene transgression, Pleistocene topography controlled wave energy and water circulation and thus in part influenced location, distribution, and recruitment of coral species that would build reefs. Caribbean Holocene reefs typically maintained a reef crest of *A. palmata*, but Florida reefs are mixed frameworks of *A. palmata* and massive head corals (e.g., Jaap, 1984; Shinn, 1980).

The massive Pleistocene shelf-margin reef indicates that conditions for regional coral growth were optimal beginning with the ca. 140 ka highstand (Table 1), yet regional margin morphologies at the end of Pleistocene marine deposition were asymmetrical (Lidz et al., 1997b). Asymmetry is best exemplified by the westward-dipping crest of the shelf-edge reef and by differences in number, shape, spacing, and relief of the outlier reefs off the lower and upper Keys. Four tracts of high-relief outlier reefs with broad (~1 km) back-reef troughs occupy the upper-slope terrace off the lower Keys (Fig. 8B). A single outlier reef with a narrow (<200 m) backreef trough on a higher-elevation terrace marks the upper Keys margin (Fig. 9A), and Holocene sediments bury four linear, low-relief features on a terrace at depths similar to the lower Keys terrace (Fig. 9B). We interpret the buried features as counterparts to those of the lower Keys outlier reefs. The jagged nature of the reflection marking their surfaces suggests the presence of corals. Their burial and sediment accumulations in leeward troughs indicate a landward sediment-transport direction. Scour by sand particles or slow burial by sand during Pleistocene transgressions may have retarded and then terminated their growth.

Minimum Age and Origin of the Upper-Slope Terrace

Relative to sea level, depths (30 to 40 m) of the upper-slope terrace surface on which the buried outlier reefs and four tracts of high-relief outliers formed are uniform margin-wide. The strong seismic reflection marking the terrace floor is distinct margin-wide (e.g., Figs. 8A, 10A; see also Lidz et al., 1997b, their Figs. 8 and 9), indicating that the surface is cemented or calcrete coated. The terrace may represent a beach formed during a regression that allowed rapid subaerial induration. Although no evidence has been recovered to signify terrace age, we can infer a youngest possible age or time of formation based on strong correlation with relief and ages of the largest Sand Key outlier reef,
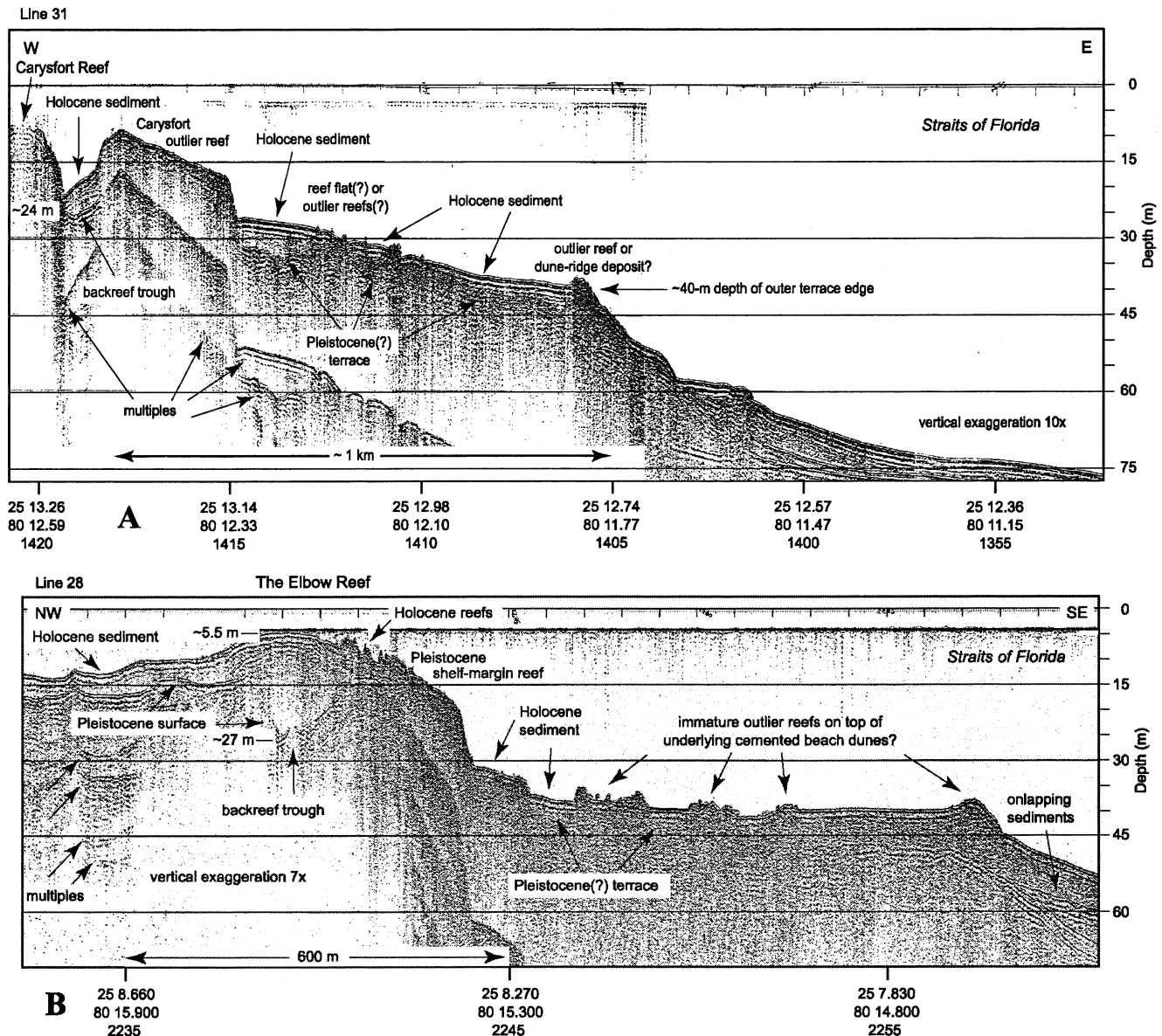
Figure 9. Seismic profiles obtained in 1991. (A) Shelf-margin features at Carysfort Reef (upper Keys just north of mapped area, Figs. 1B, 3B). Note that depth to bedrock in trough behind Carysfort outlier reef is less than depth to present upper-slope terrace (e.g., Figs. 8A, 10A). Also note depth to bedrock just in front of outlier is less than that at the Sand Key outlier reefs (Fig. 8A). See text for discussion. The Holocene section is 6 to 7 m thick on the Carysfort outlier-reef crest and 3.4 m thick on the landward crest ridge of the no. 4 outlier reef (Figs. 8A and 8B; Toscano and Lundberg, 1998). (B) Shelf-margin features at The Elbow Reef (upper Keys, Figs. 1B, 3B; modified from Lidz et al., 1997b). Note V-shaped backreef trough infilled with Holocene sediments. Also note four areas of low-relief features on upper-slope terrace. Similar seismic facies occur elsewhere on the upper Keys terrace, indicating that the features are linear. They are interpreted to represent immature outlier reefs. Latitude and longitude in decimal minutes are based on GPS coordinates. Hours (military time) adjacent to ticks are navigational correlation points along seismic line.

late Pleistocene sea-level maxima, and thickness of nearby cored sections known to have been deposited during the 140 and 125 ka highstands. By using the interglacial maxima at ca. 185 and 140 ka, which were sufficiently high (Table 1), we infer an age of roughly ca. 175 ka. A beach could well have developed and become solidified during regression from the 185 ka highstand. The lowstand would have allowed time for beach dunes to form and become cemented. Lidz et al. (1997b) have speculated that beach-dune ridges, similar to beachrock common in the Caribbean, could have been the nuclei for outlier-reef growth. Definitive beach dunes underlie Holocene reefs at Bal Harbor, locat-ed ~10 km north of Miami Beach (Fig. 1A; Shinn et al., 1977). Extensive Pleistocene beach-dune ridges exist in the Bahamas (e.g., Ball, 1967) and along the Florida shelf margin in >65 m of water (Locker et al., 1996). Corals may have initially colonized the cemented dunes during the rise that led to the 140 ka highstand. That said, however, the ter-
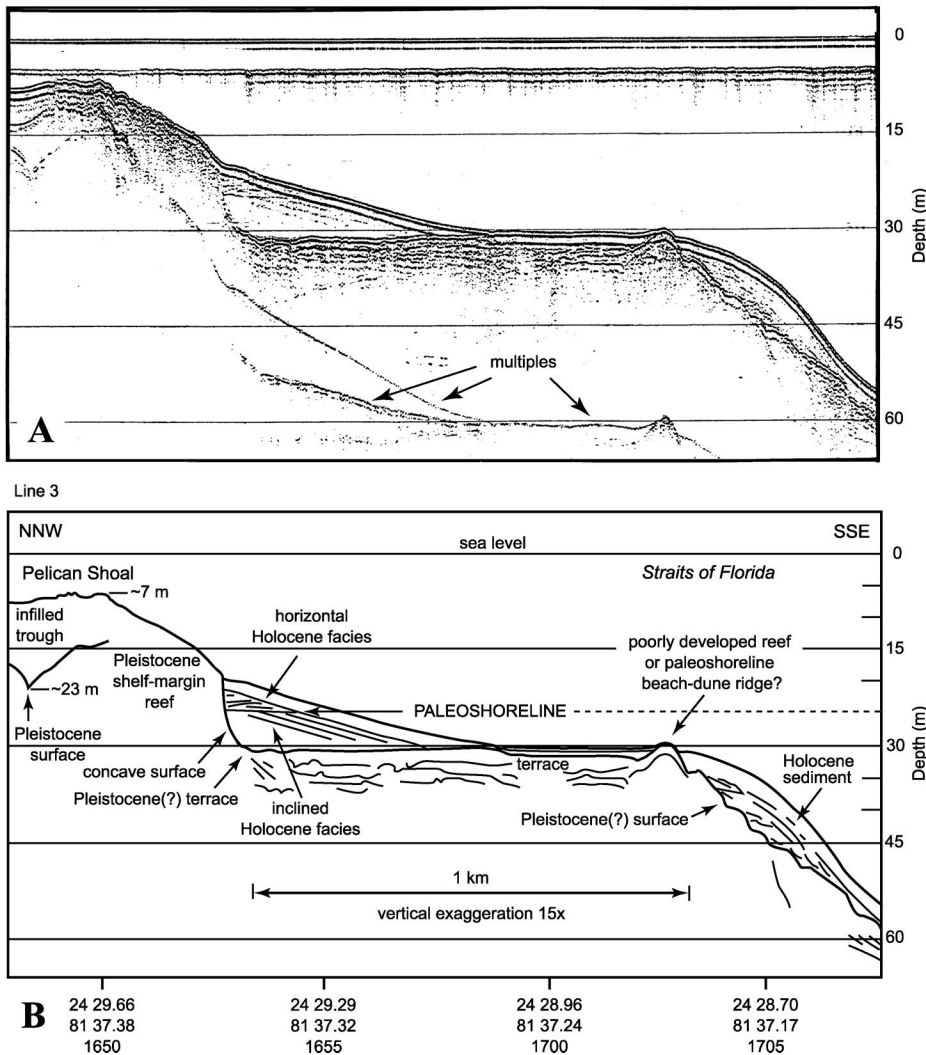
Figure 10. (A) Seismic profile obtained in 1989 and (B) interpretation show upper-slope terrace off Pelican Shoal (lower Keys, Figs. 1B, 3A). Profile crosses shelf margin nearly normal to an ~20-km-long, single outlier-reef tract east of the multiple outliers off Sand Key Reef. Note facies change in sediment wedge on terrace. Horizontal layers are interpreted to result from a stillstand that eroded tops of the inclined strata and redeposited the sands in an intertidal zone. Latitude and longitude in decimal minutes are based on GPS coordinates. Hours (military time) adjacent to ticks are navigational correlation points along seismic line.

race and dune-ridge nuclei, if present, could be older than ca. 175 ka.

The outlier reefs developed on the widest parts of the terrace (Lidz et al., 1997b). On the basis of regional data, this study adds a new, as yet unexplainable dimension. The outliers are found more often in front of the rock wall formed by the Pleistocene shelf-edge reef (Figs. 8A and 8B) than opposite kilometers-wide reentrants (Figs. 7A and 7B). Their distribution implies that there may have been a relation between sand quantity or stability and effects of prevailing energy relative to margin

curvature and capability of beach-dune formation.

Westward-Sloping Shelf and Formation of the Substage 5e Reef and Tidal Bars

Given that topographic elevations are higher to the northeast than southwest, Parker and Cooke (1944) and Parker et al. (1955) theorized that the Florida platform had tilted to the west prior to the Pleistocene. Thicker Pleistocene stratigraphic units to the southwest than northeast (e.g., Perkins, 1977, his Plate

3) would seem to confirm tilt and timing, as would lower-elevation Pleistocene bedrock in the same direction along the shelf and within Hawk Channel (Fig. 4A). On the other hand, the seismic data show margin-wide uniformity in upper-slope terrace depth, though the consistency may reflect an erosional rather than depositional origin. The inland substage 5e Key Largo Limestone and lower Keys Miami Limestone units that accumulated on the sloped bedrock also show similarity in elevation above sea level (e.g., Lidz and Shinn, 1991). The highest elevation (5.5 m) in the island chain is at Windley Key in the middle Keys (Fig. 4B; Hoffmeister and Multer, 1968).

No concrete evidence exists for platform tilting. Common southwest dips of various Pleistocene units (Perkins, 1977; Multer et al., 2002, their Fig. 10) could be attributed to factors other than tilting. Thickened units could represent areas of increased carbonate productivity, sediment importation, large-scale variations in accommodation space, or any combination thereof. An inconsistency in unit thickness depending upon location (e.g., Multer et al., 2002) could reflect differential sediment productivity, an underlying irregular undulating surface (Perkins, 1977), or local depositional or sediment-export processes. A distinct reentrant in the subsurface of Florida Bay (top of the Q3 Unit of Perkins, 1977) may have provided frequent access by Gulf Loop Currents and may have increased current scour across parts of the southwestern shelf during later Pleistocene transgressions (Multer et al., 2002). Orientation of the oölitic tidal-bar belts normal to the lower Keys shelf margin indicates that peak tidal-current velocities in the area during 5e time were high (>100 cm/s; Halley et al., 1983). Modern tidal-bar belts with similar orientation are forming in strong currents across the Quicksands (Shinn et al., 1990). Several sedimentary aspects show that southward and westward off-shelf transport is occurring today, leaving unfilled accommodation space. Sediment lobes exist seaward of Looe Key Reef (Lidz et al., 1985). A thick sediment wedge occurs southwest of the Marquesas Keys (Fig. 4B; Locker and Hine, 1995). Backreef troughs behind the Sand Key outlier reefs are unfilled (Fig. 8A). Boca Grande Channel is basically sediment-free (Shinn et al., 1990), and sediments shelf-wide are in general ~3 to 4 m thick (Fig. 4B). Physical processes and depositional controls along the shelf-margin arc were likely as different to the southwest and northeast during Pleistocene highstands as they are today. Time was also an important factor. Holocene reefs and sediments have been accumulating for
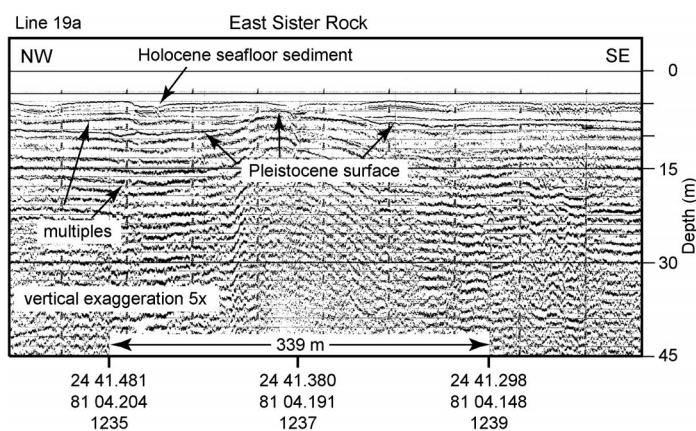
Figure 11. Seismic profile obtained in 1997 northeast of East Sister Rock (south of Vaca Key in the middle Keys, Figs. 1B, 3B) shows bedrock high not colonized by Holocene reefs but surrounded and covered by Holocene sediment. Latitude and longitude in decimal minutes are based on GPS coordinates. Hours (military time) adjacent to ticks are navigational correlation points along seismic line.

only 6 to 7 ka. Pleistocene processes and controls took place over much longer periods of time.

The Pleistocene Key Largo Limestone is time equivalent to the Quaternary Q1–Q5 Units of Perkins (1977). The coral-bearing facies of the Key Largo are largely limited to Q3, Q4, and Q5 time (Perkins, 1977; Multer et al., 2002). The latter two units correspond to the Q4 bryozoan and Q5 oölitic facies of the Miami Limestone (Hoffmeister et al., 1967). Though considered contemporaneous, the Q5 coral and two oölite facies may be so only to the extent that they all formed during 5e time. They could be sequential in age owing to bedrock slope. Two hypotheses exist as to precisely when the facies accumulated. To analyze each is to speculate beyond available data, but we note the depositional possibilities as they might have occurred during the 5e transgressive/regressive cycle to bring them to light for further investigation.

Both hypotheses assume that the Key Largo Limestone coral reef concentrated water flow and thus energy around its ends that allowed oöid precipitation (e.g., Kindinger, 1986). The first premise is that all three facies truly developed simultaneously. This argument invokes unfilled accommodation space or off-shelf oöid transport in the lower Keys to account for a 6-m-higher elevation of the oölite section in Miami than in the lower Keys (e.g., Halley and Evans, 1983). However, because the Q4 Unit unconformity is below present sea level and the oölites overlie the Q4 Unit in both areas (e.g., Perkins, 1977), the topography that focused currents for oöid formation was the Q5 part of the reef. Thus, the

second hypothesis espouses that the Q5 part of the reef grew on the highstand first, oöids in the Miami area formed next as receding waters reached suitable depths and energy, and because of bedrock slope, oöids in the lower Keys formed last when conditions there became appropriate.

Compounding timing and sequencing of events in these scenarios is that there may have been a post-maximum sea-level fluctuation of several meters within 5e time (Fig. 13). In addition, although $CaCO_3$ oöids commonly precipitate in warm, shallow (1 to 2 m) highly agitated water in open-marine settings of bank margins such as on the Great Bahama Bank (e.g., Illing, 1954; Hoffmeister, 1974; Halley et al., 1983), they can develop in deeper water. Oöids are forming at depths as great as 5 to 6 m in current-swept channels at Lee Stocking Island in the Bahamas (e.g., Dill et al., 1986). Finally, corals of the Key Largo Limestone prefer low-energy conditions and generally grow in water deeper than 5 m (Shinn et al., 1989). But *Montastrea annularis*, the dominant Key Largo species, can grow in water <5 m deep. This species is living in depths of 3 to 4 m on the outer edge of the nearshore rock ledge off the lower Keys (Marszalek, 1977).

Whereas just which depositional scenario occurred is not yet known, close association of the reef and oöid facies in the vicinity of Big Pine Key (Kindinger, 1986; Shinn et al., 1989) is clearly a result of lateral interfingering and oöids having filled divides and voids within the reef (see Fig. 12B). It is not known whether that area of the reef was dead or alive at the time of infilling. The coral component, visible in manmade "mosquito canals" on Big

Pine Key, consists mostly of staghorn sticks. Although coral reefs and precipitating oöids can coexist (e.g., at Joulters Cay, Bahamas, Halley et al. [1983] and at Caicos Island, British West Indies, Lloyd et al. [1987]), complete reef burial by oöids would likely kill the corals.

Paleoshorelines in a Rising Sea

Locker et al. (1996) investigated elevated, shore-parallel, eolian beach-dune ridges in >65 m of water south of the Marquesas Keys. Those authors interpreted the ridges as a drowned subtidal oöid-shoal complex and paleoshoreline beach dunes that formed during stillstands in the most recent rise in sea level. The rates and intervals of rise were rapid (5 to 9 m within 200–500 yr). Dated oölitic grainstones recovered from the youngest ridge indicate that oöids were precipitating as recently as ca. 14 ka, though none have been found in the Holocene record in Florida (e.g., Shinn et al., 1989). Large Bahaman oöid shoals are forming today (e.g., Halley et al., 1983). Why there are none in the Florida Holocene is a mystery.

The seismic stratigraphic contact and possible dune-ridge accumulation off Pelican Shoal (Figs. 10A and 10B) are interpreted to represent two later stillstands punctuated by a rapid-rise interval (~5 m in 100 yr). Correlation of depths of the Pelican Shoal paleoshoreline facies with the local sea-level curve shows that stillstands would have occurred at ca. 9.2 and 9.1 ka (Figs. 14A and 14B), placing this pulsation between postulated CRE-2 (catastrophic rise event) (late Pleistocene) and CRE-3 (Holocene) of Blanchon and Shaw (1995). Those authors contended that there are three gaps in the Caribbean *Acropora palmata* record, and the gaps may indicate catastrophic rise events in sea level that drowned coral reefs Caribbean-wide. CRE-3 purportedly occurred at ~15 m below present sea level, began at 7.6 ka, and had a magnitude of 6.5 m in a period of <140 ± 50 yr. Blanchon and Shaw (1995) argued that the *A. palmata* framework was reestablished 5 m up-section at the end of CRE-3. At a position of minus 15 m in Florida, sea level had yet to flood the shelf (Fig. 4A). A 6.5 m rise would have moved the shoreline to the 8.5-m-depth contour. [14]C dates on corals, calcrete, and mangrove peat shelf-wide that have adequate temporal resolution do not support a rapid rise at 7.6 ka (e.g., Shinn et al., 1977; Robbin, 1984). Laterally adjacent mangrove peat and calcrete recovered from 7.2 m below sea level and from beneath *A. palmata* at Alligator Reef
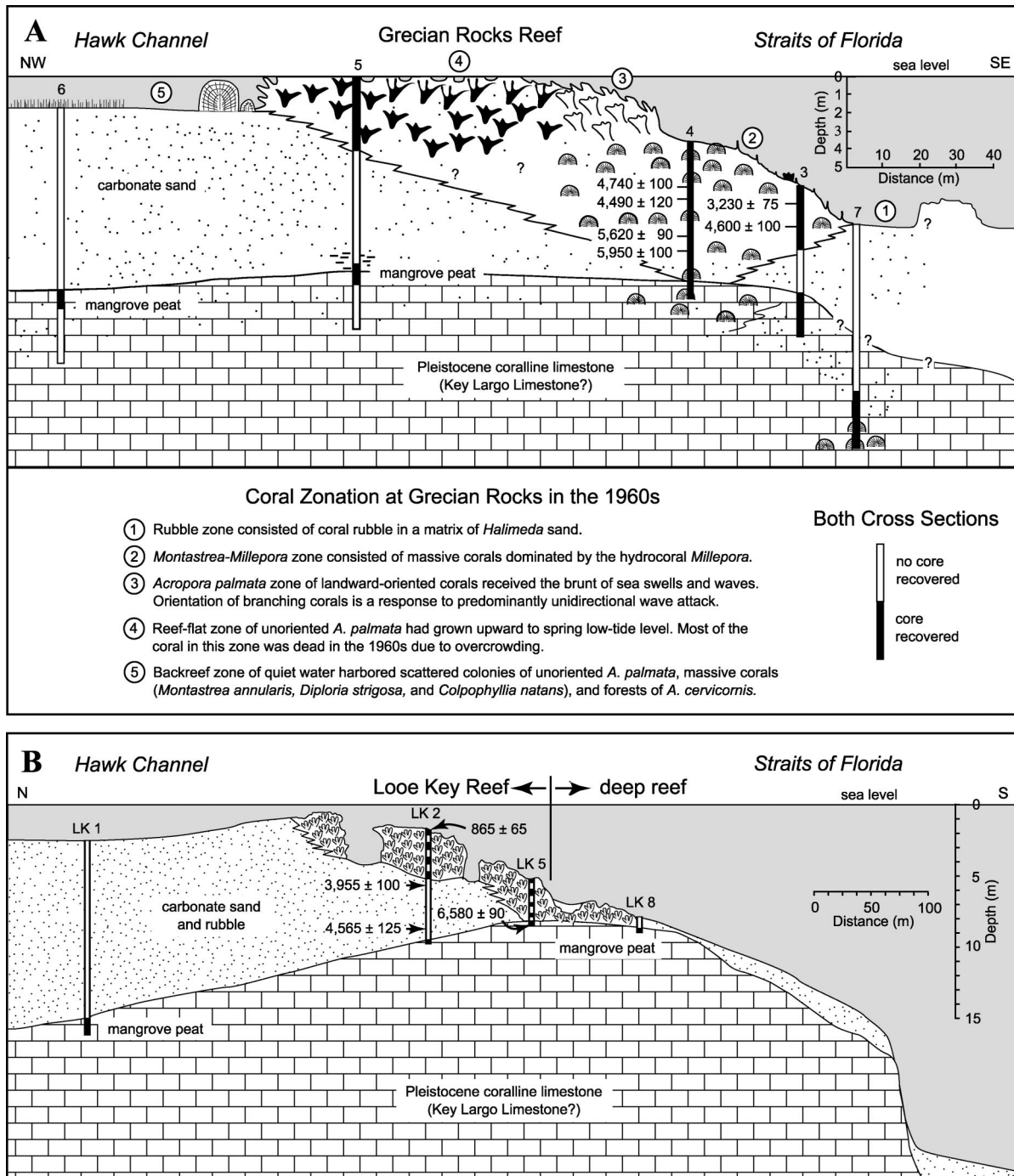
Figure 12. Cross sections of Grecian Rocks Reef (upper Keys, location in Figs. 3B and 15A) and Looe Key Reef (lower Keys, Fig. 3A) and ^{14}C ages of corals recovered in cores. (A) Coral zonation at Grecian Rocks in the 1960s showed five distinct zones (Shinn, 1963; modified from Shinn, 1980). Field observations in 2002 revealed most of the corals including hydrocorals were dead. (B) Coral growth at Looe Key Reef began on a bedrock ridge of Pleistocene limestone and backstepped over a bedrock depression filled with carbonate sand and rubble (modified from Shinn et al., 1981; Lidz et al., 1985). Note natural lateral spaces or divides between coral reef sections. Cores are designated LK with a number. ^{14}C ages of 6580 ± 90 yr at base of LK5 and 5950 ± 100 yr in Grecian Rocks core 4 indicate that coral growth began sooner in the lower than upper Keys. Note depths and locations of mangrove peat in both figures. Peat forms at very low wave-energy shorelines. The deepest peat found so far on the reef tract was recovered in LK1.

TABLE 1. DATA AND ASSUMPTIONS USED TO INFER YOUNGEST POSSIBLE AGE OF UPPER-SLOPE TERRACE

Material dated	Dates (ka)	Geologic age	Coral depths (m)[†]	Thickness in outlier reef (m)	Maximum highstand (m)[†]	Authors
A. palmata, C. natans	8.9–6.9	Holocene	−12.3 to −8.9	3.4	0	Toscano and Lundberg (1998)
1 *A. palmata*, 1 *C. natans*, 8 *M. annularis*	84.5–80.9	5a[‡]	−24.0 to −12.3	11.7	−9	Ludwig et al. (1996), Toscano and Lundberg (1999)
3 *M. annularis*, 1 *A. palmata*	94.4–90.6	5b[‡]	−19.8 to −15.5	4.3	−14 to −10	Toscano and Lundberg (1999)
M. annularis	106.5	5c[‡]	−21.7	?	−15	Toscano and Lundberg (1999), Chappell (1974)
M. annularis, top of Q5 Unit	~125	5e[‡]	~+5.5		~+10.6	Hoffmeister and Multer (1968), Perkins (1977), Halley and Evans (1983)
(highstand)	~125	5e[‡]	?			Hoffmeister and Multer (1968)
Top of Q4 Unit, Big Pine Key (pelecypod *Mercenaria*)	~134		−5.0			Mitterer (1975), Perkins (1977)
(highstand)	140		?			Chappell (1974)
Top of Q3 Unit, Big Pine Key (pelecypod *Mercenaria*)	~180		−8.0			Mitterer (1975), Perkins (1977)
(highstand)	185					Chappell (1974)
(highstand)	220		Not identified in Florida			Chappell (1974)
Top of Q2 Unit, Big Pine Key (pelecypod *Mercenaria*)	~236		−37.5			Mitterer (1975), Perkins (1977)

Notes: Coral dates except for 125 ka *M. annularis* are from Sand Key outlier reef. Upper-slope terrace on which outlier reefs grew is 30–40 m below present sea level. Largest outlier reef is ~28–30 m (mean 29 m) in relief. Assumptions: Relative to present sea level, sea-level maximum (−37.5 m, Perkins, 1977) in the Sand Key Reef area at the end of Q2 time was not high enough to form the nearly horizontal, smooth, ~2.5-km-wide upper-slope terrace surface. The 324 ka Q1 Unit surface in the same area is deeper (~−48 m). By inference then, given the tabulated data, the youngest time the terrace could have formed would have been during the 185 ka regression. The age of the terrace surface could be ca. 175 ka. The interval between highstands at 185 and 140 ka would have been sufficient for postulated beach dunes to form and become cemented, allowing initial colonization by outlier-reef corals during the subsequent transgression. If the terrace age is ca. 175 ka, and given a mean outlier-reef relief of 29 m and the 21.7-m-thick dated interval in the Sand Key outlier reef, a reasonable assumption is that the initial 7.3 m of outlier-reef accumulation developed during the 140 ka and substage 5e transgressions. Without reference to any particular coral species or growth rate, it is clear from the combined thickness (~8 m, Perkins, 1977, his Plate 3) of the Q4 and Q5 Units in the Sand Key Reef area that there was ample time for a comparable 7.3 m of Q4 and Q5 (5e) coral framework to accumulate on the outlier reefs.
    [†]Depths relative to present sea level. Depths of Q2–Q4 unconformities from Big Pine Key core 56 of Perkins (1977). Elevation for top of Q5 Unit is highest elevation in the keys at Windley Key (Lidz and Shinn, 1991).
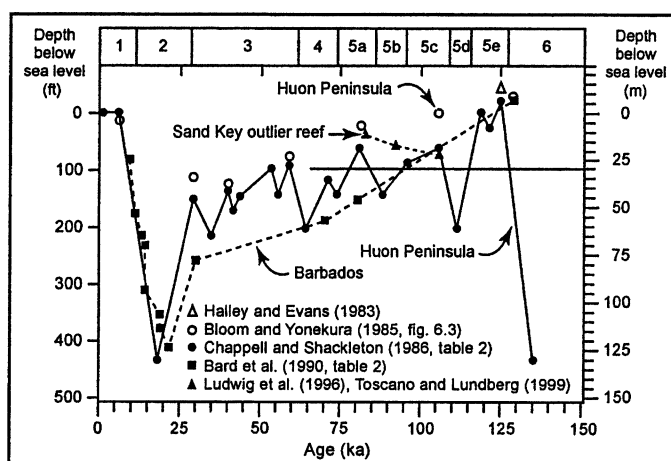   [‡]Substages of oxygen isotope Stage 5.

Figure 13. Sea-level curves for oxygen isotope Stages 6–1. The Key Largo Limestone reef (middle and upper Keys) and Miami Limestone oölite units (lower Keys and beneath Miami) belong to substage 5e. Sand Key outlier reef no. 4 contains corals that date to substages 5c, 5b, and 5a (Table 1). Horizontal line represents highest elevation of upper-slope terrace.

yielded ^{14}C ages of 7595 ± 85 and 7280 ± 130 yr, respectively (Robbin, 1984). Robbin calculated a rate of sea-level rise of 1 m per 1 ka at Alligator Reef from ca. 7.3 ka to the present. Shinn et al. (1977) derived similar rates for reef accretion in the Big Pine Shoal area. In a thorough analysis of age data for mangrove peat and calcrete, and growth rates and age data for *A. palmata* from Florida, Barbados, and the Bahamas, Toscano and Lundberg (1998) found that age and elevation ranges of CRE-3 are well represented by apparently continuous coral growth. They concluded that at no point in the 12 ka Florida-Bahamas record did sea-level rise approach catastrophic rates or rates at which *A. palmata* or a mixed framework would not keep pace with rising sea level. We agree.

As the Holocene sea encroached upon the shelf, water flowed in various directions depending on the Pleistocene topography. Contours of the Pleistocene surface are thus proxies for positions of Holocene shorelines prior
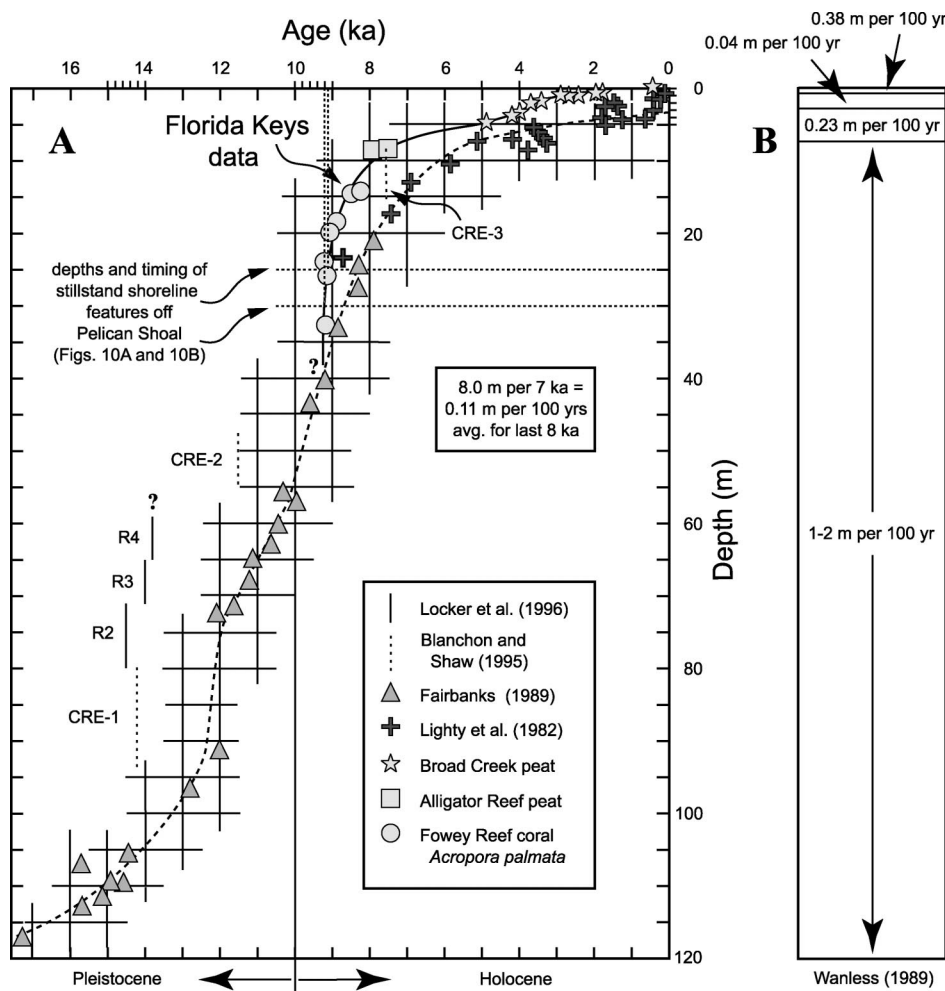
Figure 14. Well-constrained sea-level curve for the Florida reef tract based on local proxy data (¹⁴C ages) as modified (Lidz and Shinn, 1991) from the curve of Robbin (1984). (A) Data from 8 ka to the present are considered reliable. Note depths and ages of interpreted stillstand facies off Pelican Shoal. R2–R4 = interpreted rapid sea-level rises (Locker et al., 1996). CRE-1–CRE-3 = proposed catastrophic rise events (Blanchon and Shaw, 1995). (B) Rates of sea-level rise. Upper part of figure shows actual rise measured by tide gauges at Key West.

to colonization by Holocene corals. Flooding began to the southwest and progressed northeastward because of topographic slope (Fig. 4A; see flood-series figures in Lidz and Shinn, 1991). Relative to present sea level, contours shallower than 10 m show shoreline positions since 8 ka and are well constrained by ¹⁴C dates on local mangrove peat, calcrete, and *A. palmata* (Fig. 14A; Robbin and Stipp, 1979; Robbin, 1981, 1984). Dates of contours deeper than 10 m and older than 8 ka are less precise, but the older shorelines existed as the bedrock flooded. Though flooding gradually produced many shoreline configurations, color groups in Figure 4A show three obvious "flood stages": (1) at minus 18 m (location 1 on the map), (2) at minus 14 m (location 2),

and (3) at minus 10 m (location 3). When sea level was 18 m lower than today, the exposed shelf including the Marquesas-Quicksands ridge and bedrock beneath Florida and Biscayne Bays was contiguous land. At minus 14 m, parts of the lower Keys outer shelf flooded, and the mainland area extended as a broad curved promontory projecting into the Gulf of Mexico. Islands existed at Sand Key, Looe Key, and Rock Key Reefs (Figs. 3A and 8B), and Hawk Channel was filled as far east as Looe Key Reef. Essentially all named shoals and reefs along the outer shelf were once Holocene islands built of Pleistocene limestone, then later coated by Holocene reefs. At minus 10 m, water breached the margin in the vicinity of Sombrero Key and Tennessee Reefs

(Fig. 3B), advanced up Hawk Channel to off the west end of Long Key, and ponded in areas off the middle and upper Keys. Bahia Honda Channel was flooded. The Marquesas-Quicksands ridge and the lower Keys were still joined. As sea level reached minus 6 m, water in Boca Grande Channel severed the terrestrial connection between the ridge and the lower Keys and reduced the emergent part of the ridge to four islands at its east end. The first outer-shelf Holocene corals had become established off the lower and middle Keys and were beginning to colonize upper Keys bedrock highs (Shinn et al., 1977). At minus 4 m at ca. 4.4 ka, three of the Marquesas-Quicksands ridge islands and all outer-shelf islands disappeared. Water flowed throughout Hawk Channel, low areas in the Key Largo Limestone became tidal passes, and only the inner-shelf areas nearest the highest parts of the keys remained above sea level. At ca. 2 ka, sea level was ~0.5 m lower than present, Florida and Biscayne Bays were flooded, and Rodriguez Key and Tavernier Key banks had evolved from mud banks to branching-coral and coralline-algae banks (Fig. 5A; Turmel and Swanson, 1976). The keys looked much as they do today.

Holocene Sediments and Reefs

Modern carbonate sand bodies associated with bank, platform, or shelf margins reflect the orientation, exposure, and topographic complexity of those margins. Winds, waves, currents, tides, biogenic barriers, and rock ridges or terraces control sediment production, type, transport, and sand-body geometry, orientation, and size (Halley et al., 1983). Ball (1967) classified sand accretions of Florida and the Bahamas into four groups: tidal-bar belts, marine sand belts, eolian ridges or dunes, and platform-interior blankets. In Florida, a shelf-margin environment, typical tidal-bar belts are seen in the Pleistocene oölite units and in the modern *Halimeda* sands of the Quicksands, so named because the sands are in constant motion (Shinn et al., 1990). White Bank off north Key Largo (Figs. 3B and 15A) is a backreef marine sand belt that parallels the shelf margin seaward of Hawk Channel. Composed of coral, algal, and molluscan sands, the sand belt is 1 to 2 km wide and 40 km long (Enos, 1977). Both active (rippled) and stable bottoms (covered by sea grasses) occur at similar depths of 1 to 3 m, indicating that local hydrologic conditions control formation of large scattered sand waves. The sand belt is cross-bedded with a steeper landward slope (Enos, 1977), suggest-
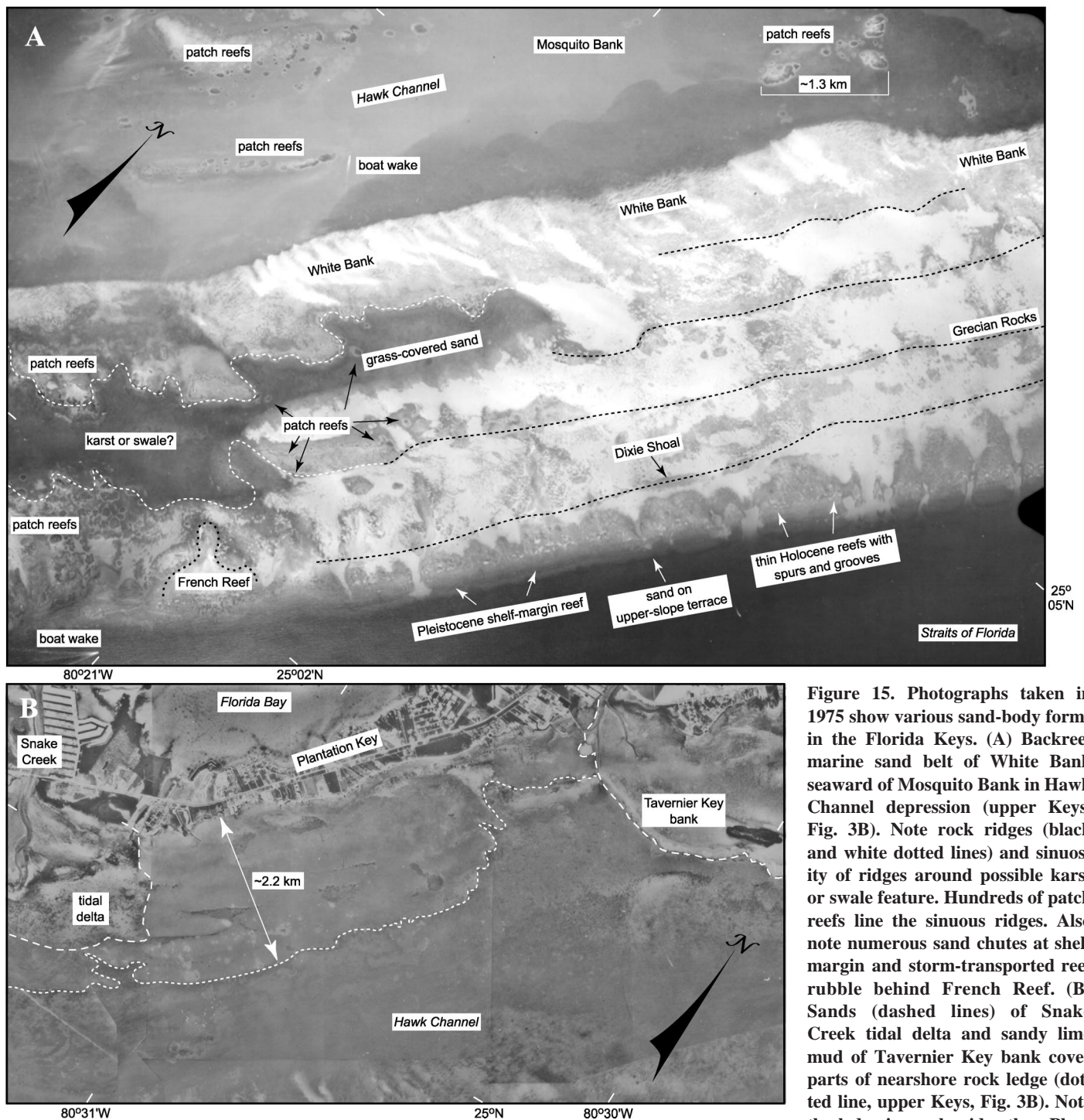
Figure 15. Photographs taken in 1975 show various sand-body forms in the Florida Keys. (A) Backreef marine sand belt of White Bank seaward of Mosquito Bank in Hawk Channel depression (upper Keys, Fig. 3B). Note rock ridges (black and white dotted lines) and sinuosity of ridges around possible karst or swale feature. Hundreds of patch reefs line the sinuous ridges. Also note numerous sand chutes at shelf margin and storm-transported reef rubble behind French Reef. (B) Sands (dashed lines) of Snake Creek tidal delta and sandy lime mud of Tavernier Key bank cover parts of nearshore rock ledge (dotted line, upper Keys, Fig. 3B). Note the ledge is much wider than Plantation Key.

ing landward sand transport. Ball et al. (1967) documented landward accretion after passage of Hurricane Donna in 1960. Pleistocene oölitic beach-dune ridges exist in 65 to 124 m of water off the Marquesas Keys (Locker et al., 1996). Florida lacks a Holocene platform-interior sand blanket, though the Q

Units underlying Florida Bay may represent Pleistocene blankets. Other types of sand bodies are also found on the shelf. Lobate tidal deltas generated by tidal currents occur on the seaward side of intra-key tidal passes, particularly in the larger channels (Figs. 5B and 15B). Elongate areas of coral rubble have

formed behind the Holocene shelf-margin reefs where storms have transported coarse sediments landward (Figs. 8B and 15A), and sand chutes (Enos, 1977) are present on the shelf-margin reef (Fig. 15A).

The type of Holocene carbonate sediments along the south Florida shelf varies from lime

muds (Hawk Channel) to mud-bearing sands (northeast) to coarse-grained sands (southwest) to *Halimeda* sands (Quicksands) to coral rubble (outer shelf). Much like coral zonation, sediment type is dependent upon geographic factors, marine topography, and local processes. Relative to sea level and to elevations of shelf bedrock off the lower Keys, bedrock off the upper Keys is shallower (avg. range, 8 to 12 m), and a higher elevation at the submerged shelf-margin reef crest (~5 to 8 m) offers some degree of protection from high-energy waves. Narrow creeks through the elongate island of Key Largo limit significant tidal flushing. A restricted environment and onshore prevailing energy in the upper Keys ensures a lengthy residence time for accumulated sediments. Consequently, sediments on the upper Keys shelf are a mixture of fine and coarse mud-bearing sands.

Direction of energy in the lower Keys, however, is tangential to the coast, and nearshore currents (vs. the Gulf Stream) flow westward. Shelf bedrock off the lower Keys is deeper (avg. range, 12 to 18 m), and the area is open and exposed to multiple hydrologic processes. A lower elevation at the shelf-margin crest (~7 to 15 m) offers less protection from offshore currents. Current velocities between the Straits of Florida and Gulf of Mexico are strong and reverse with the tides, yet a Gulf-to-Atlantic gradient in sea level allows net nontidal flow of water across the shelf to the ocean through numerous wide tidal passes (Smith, 1994). This setting allows winnowing of fine-grained material and transport of sediments west and southwest off the shelf, leaving predominantly coarse-grained sands in the area of the lower Keys.

The most important factor that affected Florida's Holocene reefs during rising sea level was a concurrent change in water quality. Increasing water depth moved the surf zone landward, increased exposure to cold Gulf of Mexico waters, and decreased light attenuation, causing coral species within reefs to change and coral reefs to backstep. Head corals dominated when the exposed shelf-edge ridge produced calm back-ridge conditions on the outer shelf. With rising water and increasing wave energy across the shelf, *Acropora palmata* took over and grew landward. Deteriorating water quality upon flooding of Florida and Biscayne Bays at ca. 2 ka and tidal and storm-driven mixing of bay and Gulf of Mexico waters with the reefs caused the coral ecosystem to decline. Today, human activities compound the situation. The relict Holocene reef framework has become the most recent component of the submarine geomorphology.

Withdrawal of the sea, when it occurs, will cement and coat sediments with calcrete, ensuring addition of the sedimentary section to the Quaternary record.

CONCLUSIONS

An updated regional map of Pleistocene topography seaward and westward of the Florida Keys details greater accommodation space to the southwest than to the northeast. Depending on location along the shelf, differences in physical, depositional, and off-shelf sediment-transport processes during numerous Pleistocene highstands likely controlled the cumulative inconsistency in elevation. Average bedrock depth below sea level ranges from ~8 to 12 m off the upper Keys, ~12 to 18 m off the lower Keys, and ~18 to 24 m off the Marquesas-Quicksands ridge. Average bedrock depth on the ridge ranges from ~6 to 8 m. The deepest areas are reentrants in the discontinuous shelf-margin reef.

Despite bedrock slope, the regional Holocene map shows that sediment is generally ~3 to 4 m thick shelf-wide. In the lower Keys, deep water, strong nearshore westward-trending currents, open exposure to high wave energies, and net Gulf-to-Atlantic flow result in off-bank sediment transport. Major Holocene sand bodies include tidal deltas, tidal-bar belts, storm-transported coral rubble, and a marine sand belt. Tidal-bar belts and dune-ridge complexes are found in the Pleistocene record.

Tidal-pass channels in the Florida Keys show contrasts and consistencies. Water depth to bedrock within a given channel is not related to width of that channel. Relative to sea level, bedrock in the Bahia Honda Channel may be the deepest in the keys. Bedrock in the widest tidal pass (Moser Channel, ~14.5 km) is only as deep (~4.5 m) as in other much narrower middle Keys passes (Key Largo Limestone). Narrow channels in the lower Keys Miami Limestone represent tidal-bar swales. All channels are Pleistocene.

A youngest possible age of ca. 175 ka is inferred for formation of the region-wide 30- to 40-m-deep upper-slope terrace. The terrace is presumed to represent a beach formed during a regression.

Aerial photographs document a nearshore rock ledge, bands of rock ridges on the outer shelf and terrace, four tracts of high-relief outlier reefs on the lower Keys terrace, and four buried low-relief tracts on the upper Keys terrace. Seismic and photographic evidence indicate that the high-relief outlier reefs extend >200 km along the shelf margin. The outlier

reefs developed more often and more extensively opposite the discontinuous shelf-margin reef but not opposite kilometers-wide reentrants.

Pleistocene coral reef growth on the upper-slope terrace was probably margin-wide at its inception, inferred to have been at ca. 140 ka, but produced asymmetrical geomorphic patterns when Pleistocene marine deposition ceased after the ca. 80 ka highstand. Asymmetry is reflected in a deeper shelf-margin reef crest to the southwest than to the northeast and in the number, shape, spacing, and relief of outlier reefs off the lower and upper Keys. Asymmetry may have been due in part to different effects of prevailing southeasterly winds and waves on reef development and on local physical processes along the arcuate margin.

On a regional scale, the primary controls on accumulation of Holocene coral reefs and sediments were a sloping Pleistocene landscape, a curved shelf margin, prevailing energy from the southeast, a rising sea level, and eventual flooding of Florida and Biscayne Bays. On a local scale, primary controls on the location and distribution of reefs and sands and on the type of coral species were Pleistocene topography and Holocene wave energy.

REFERENCES CITED

Ball, M.M., 1967, Carbonate sand bodies of Florida and the Bahamas: Journal of Sedimentary Petrology, v. 37, p. 556–591.

Ball, M.M., Shinn, E.A., and Stockman, K.W., 1967, The geologic effects of Hurricane Donna in south Florida: Journal of Geology, v. 75, p. 583–597.

Bard, E., Hamelin, B., Fairbanks, R.G., Zindler, A., Mathieu, G., and Arnold, M., 1990, U/Th and ¹⁴C ages of corals from Barbados and their use for calibrating the ¹⁴C time scale beyond 9000 yr B.P.: Nuclear Instruments and Methods in Physics Research, v. B52, p. 461–468.

Blanchon, P., and Shaw, J., 1995, Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse: Geology, v. 23, p. 4–8.

Bloom, A.L., and Yonekura, N., 1985, Coastal terraces generated by sea-level change and tectonic uplift, in Woldenberg, M.J., ed., Models in geomorphology: Winchester, Massachusetts, Allen and Unwin, p. 139–153.

Brooks, G.R., and Holmes, C.W., 1989, Recent carbonate slope sediments and sedimentary processes bordering a nonrimmed platform: Southwest Florida continental margin, in Crevello, P.D., et al., eds., Controls on carbonate platform and basin development: Society of Economic Paleontologists and Mineralogists Special Publication 44, p. 259–274.

Chappell, J., 1974, Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea-level changes: Geological Society of America Bulletin, v. 85, p. 553–570.

Chappell, J., and Shackleton, N.J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Davies, T.D., 1980, Peat formation in Florida Bay and its significance in interpreting the Holocene vegetational and geological history of the bay area [Ph.D. thesis]: University Park, Pennsylvania State University, 316 p.

Davis, R.A., Hine, A.C., and Shinn, E.A., 1992, Holocene coastal development on the Florida Peninsula, in Fletcher, C., and Wehmiller, J., eds., Quaternary coasts of the United States: Marine and lacustrine systems: SEPM (Society for Sedimentary Geology) Special Publication 48, p. 193–212.

Dill, R.F., Shinn, E.A., Jones, A.T., Kelly, K., and Steinen, R.P., 1986, Giant subtidal stromatolites forming in normal salinity waters: Nature, v. 324, p. 55–58.

Dustan, P., 1985, Community structure of reef-building corals in the Florida Keys: Carysfort Reef, Key Largo and Long Key Reef, Dry Tortugas: Atoll Research Bulletin, v. 288, p. 1–27.

Enos, P., 1977, Holocene sediment accumulations of the south Florida shelf margin, part I, in Enos, P., and Perkins, R.D., eds., Quaternary sedimentation in south Florida: Geological Society of America Memoir 147, p. 1–130.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep ocean circulation: Nature, v. 342, p. 637–642.

Ford, D.C., and Williams, P.W., 1992, Karst geomorphology and hydrology: New York, Chapman and Hall, 601 p.

Ginsburg, R.N., and James, N.P., 1974, Holocene carbonate sediments of continental shelves, in Burke, C.A., and Drake, C.L., eds., The geology of continental margins: New York, Springer-Verlag, p. 137–156.

Ginsburg, R.N., and Shinn, E.A., 1964, Distribution of the reef-building community in Florida and the Bahamas [abs.]: American Association of Petroleum Geologists Bulletin, v. 48, p. 527.

Grasmueck, M., and Weger, R., 2002, 3D GPR reveals complex internal structure of Pleistocene oolitic sandbar: The Leading Edge, July 2002, p. 634–639.

Halley, R.B., and Evans, C.E., 1983, The Miami Limestone: A guide to selected outcrops and their interpretation (with a discussion of diagenesis in the formation): Miami, Florida, Miami Geological Society, 65 p.

Halley, R.B., Harris, P.M., and Hine, A.C., 1983, Bank margin environment, in Scholle, P.A., et al., eds., Carbonate depositional environments: Tulsa, Oklahoma, American Association of Petroleum Geologists, AAPG Memoir 33, p. 463–506.

Halley, R.B., Vacher, H.L., and Shinn, E.A., 1997, Geology and hydrogeology of the Florida Keys, in Vacher, H.L., and Quinn, T., eds., Geology and hydrogeology of carbonate islands, Developments in Sedimentology 54: Amsterdam, Elsevier Science, p. 217–248.

Hallock, P., and Schlager, W., 1986, Nutrient excess and the demise of coral reefs and carbonate platforms: PALAIOS, v. 1, p. 389–398.

Hine, A.C., and Mullins, H.T., 1983, Modern carbonate shelf-slope breaks, in Stanley, D.J., and Moore, G.T., eds., The shelfbreak: Critical interface on continental margins: Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 169–188.

Hoffmeister, J.E., 1974, Land from the sea, the geologic story of south Florida: Coral Gables, Florida, University of Miami Press, 143 p.

Hoffmeister, J.E., and Multer, H.G., 1968, Geology and origin of the Florida Keys: Geological Society of America Bulletin, v. 79, p. 1487–1502.

Hoffmeister, J.E., Stockman, K.W., and Multer, H.G., 1967, Miami Limestone of Florida and its Holocene Bahamian counterpart: Geological Society of America Bulletin, v. 78, p. 175–190.

Hudson, J.H., 1985, Growth rate and carbonate production in Halimeda opuntia, Marquesas Keys, Florida, in Toomey, D.F., and Nitecki, M.H., eds., Paleoalgology: Contemporary research and applications: Berlin, Springer-Verlag, p. 257–263.

Illing, L.V., 1954, Bahamian calcareous sands: American Association of Petroleum Geologists Bulletin, v. 38, p. 1–95.

Incze, M.L., 1998, Petrophysical properties of shallow-water carbonates in modern depositional and shallow subsurface [Ph.D. thesis]: Coral Gables, University of Miami, 405 p.

Jaap, W.C., 1984, The ecology of the south Florida coral reefs: A community profile: U.S. Department of the Interior, Fish and Wildlife Service Report FWS/OBS-82/08 and Minerals Management Service Report MMS 84–0038, 138 p.

James, N.P., and Choquette, P.W., eds., 1988, Paleokarst: New York, Springer-Verlag, 416 p.

Kindinger, J.L., 1986, Geomorphology and tidal-belt depositional model of lower Florida Keys [abs.]: American Association of Petroleum Geologists Bulletin, v. 70, p. 607.

Kindinger, J.L., Davis, J.B., and Flocks, J.G., 1999, Geologic controls on the formation of lakes in north-central Florida, in Pitman, J.K., and Carroll, A.R., eds., Modern and ancient lake systems: Salt Lake City, Utah Geological Association Guidebook 26, p. 9–30.

Lidz, B.H., and Shinn, E.A., 1991, Paleoshorelines, reefs, and a rising sea: South Florida, U.S.A: Journal of Coastal Research, v. 7, p. 203–229.

Lidz, B.H., Robbin, D.M., and Shinn, E.A., 1985, Holocene carbonate sedimentary petrology and facies accumulation, Looe Key National Marine Sanctuary, Florida: Bulletin of Marine Science, v. 36, p. 672–700.

Lidz, B.H., Hine, A.C., Shinn, E.A., and Kindinger, J.L., 1991, Multiple outer-reef tracts along the south Florida bank margin: Outlier reefs, a new windward-margin model: Geology, v. 19, p. 115–118.

Lidz, B.H., Shinn, E.A., Hansen, M.E., Halley, R.B., Harris, M.W., Locker, S.D., and Hine, A.C., 1997a, Sedimentary and biological environments, depth to Pleistocene bedrock, and Holocene sediment and reef thickness from Molasses Reef to Elbow Reef, Key Largo, south Florida: U.S. Geological Survey Miscellaneous Investigations Series Map I-2505, scale 1:24,000, 3 sheets.

Lidz, B.H., Shinn, E.A., Hine, A.C., and Locker, S.D., 1997b, Contrasts within an outlier-reef system: Evidence for differential Quaternary evolution, south Florida windward margin, U.S.A.: Journal of Coastal Research, v. 13, p. 711–731.

Lighty, R.G., Macintyre, I.G., and Stuckenrath, R., 1982, Acropora palmata reef framework: A reliable indicator of sea level in the western Atlantic for the past 10,000 years: Coral Reefs, v. 1, p. 125–130.

Lloyd, R.M., Perkins, R.D., and Kerr, S.D., 1987, Beach and shoreface ooid deposition on shallow interior banks, Turks and Caicos Islands, British West Indies: Journal of Sedimentary Petrology, v. 57, p. 976–982.

Locker, S.D., and Hine, A.C., 1995, Late Quaternary sequence stratigraphy, south Florida margin: Proceedings, Annual Ocean Technology Conference, 27th: Dallas, The Offshore Technology Conference, p. 319–327.

Locker, S.D., Hine, A.C., Tedesco, L.P., and Shinn, E.A., 1996, Magnitude and timing of episodic sea-level rise during the last deglaciation: Geology, v. 24, p. 827–830.

Ludwig, K.R., Muhs, D.R., Simmons, K.R., Halley, R.B., and Shinn, E.A., 1996, Sea-level records at ~80 ka from tectonically stable platforms: Florida and Bermuda: Geology, v. 24, p. 211–214.

Mallinson, D., Hine, A., Hallock, P., Locker, S., and Shinn, E., 2003, Development of small carbonate banks on the south Florida platform margin: Response to sea level and climate change: Marine Geology (in press).

Marszalek, D.S., 1977, Florida reef tract marine habitats and ecosystems: Maps published in cooperation with State of Florida Department of Natural Resources; U.S. Department of Interior Bureau of Land Management, New Orleans Outer Continental Shelf Office; and University of Miami Rosenstiel School of Marine and Atmospheric Science, scale 1:30,000, 9 sheets.

Mitterer, R.M., 1975, Ages and diagenetic temperatures of Pleistocene deposits of Florida based on isoleucine epimerization in Mercenaria: Earth and Planetary Science Letters, v. 28, p. 275–282.

Mullins, H.T., Gardulski, A.F., Hine, A.C., Melillo, A.J., Wise, S.W., and Applegate, J., 1988, Three-dimensional sedimentary framework of the carbonate ramp slope of central-west Florida: A sequential seismic stratigraphic perspective: Geological Society of America Bulletin, v. 100, p. 514–533.

Multer, H.G., Gischler, E., Lundberg, J., Simmons, K.R., and Shinn, E.A., 2002, Key Largo Limestone revisited: Pleistocene shelf-edge facies, Florida Keys, USA: Facies, v. 46, p. 229–272.

National Oceanic and Atmospheric Administration, 1993, Florida Keys, Sombrero Key to Sand Key: National Ocean Survey, National Coast and Geodetic Survey, Chart 11442, scale 1:80,000, 1 sheet.

Parker, G.G., and Cooke, C.W., 1944, Late Cenozoic resources of southeastern Florida, with a discussion of

the ground water: Florida Geological Survey Bulletin, no. 27, p. 1–119.

Parker, G.G., Hoy, N.D., and Schroeder, M.C., 1955, Geology, *in* Parker, G.G., et al., eds., Water resources of southeastern Florida: U.S. Geological Survey Water Supply Paper 1255, p. 57–125.

Parks, P., 1968, The railroad that died at sea, Florida East Coast Railway Flagler System, the Florida East Coast's Key West Extension: Key West, Florida, Langley Press, Inc., 45 p.

Perkins, R.D., 1977, Depositional framework of Pleistocene rocks in south Florida, part II, *in* Enos, P., and Perkins, R.D., eds., Quaternary sedimentation in south Florida: Geological Society of America Memoir 147, p. 131–198.

Robbin, D.M., 1981, Subaerial CaCO$_3$ crust: A tool for timing reef initiation and defining sea level changes: Proceedings, International Coral Reef Symposium, 4th, Manila, Philippines, v. 1, p. 575–579.

Robbin, D.M., 1984, A new Holocene sea level curve for the upper Florida Keys and Florida reef tract, *in* Gleason, P.J., ed., Environments of south Florida: Present and past: Miami, Florida, Miami Geological Society Memoir 2, p. 437–458.

Robbin, D.M., and Stipp, J.J., 1979, Depositional rate of laminated soilstone crusts, Florida Keys: Journal of Sedimentary Petrology, v. 49, p. 175–180.

Sanford, S., 1909, The topography and geology of southern Florida: Florida Geological Survey Annual Report, v. 2, p. 175–231.

Shinn, E.A., 1963, Spur and groove formation on the Florida reef tract: Journal of Sedimentary Petrology, v. 33, p. 291–303.

Shinn, E.A., 1980, Geologic history of Grecian Rocks, Key Largo Coral Reef Marine Sanctuary: Bulletin of Marine Science, v. 30, p. 646–656.

Shinn, E.A., Hudson, J.H., Halley, R.B., and Lidz, B.H., 1977, Topographic control and accumulation rate of some Holocene coral reefs, south Florida and Dry Tortugas: Proceedings, International Coral Reef Symposium, 3rd, Miami, Florida, Biology, v. 2, p. 1–7.

Shinn, E.A., Hudson, J.H., Robbin, D.M., and Lidz, B.H., 1981, Spurs and grooves revisited, construction versus erosion, Looe Key Reef, Florida: Proceedings, International Coral Reef Symposium, 4th, Miami, Florida, Biology, v. 1, p. 475–483.

Shinn, E.A., Lidz, B.H., Kindinger, J.L., Hudson, J.H., and Halley, R.B., 1989, Reefs of Florida and the Dry Tortugas: A guide to the modern carbonate environments of the Florida Keys and the Dry Tortugas: Washington, D.C., American Geophysical Union, International Geological Congress Field Trip Guidebook T176, 55 p.

Shinn, E.A., Lidz, B.H., and Holmes, C.W., 1990, Highenergy carbonate sand accumulation, the Quicksands, southwest Florida Keys: Journal of Sedimentary Petrology, v. 60, p. 952–967.

Shinn, E.A., Reese, R.S., and Reich, C.D., 1994, Fate and pathways of injection-well effluent in the Florida Keys: U.S. Geological Survey Open-File Report 94–276, 116 p.

Shinn, E.A., Reich, C.D., Locker, S.D., and Hine, A.C., 1996, A giant sediment trap in the Florida Keys: Journal of Coastal Research, v. 12, p. 953–959.

Smith, N.P., 1994, Long-term Gulf-to-Atlantic transport through tidal channels in the Florida Keys: Bulletin of Marine Science, v. 54, p. 602–609.

Toscano, M.A., 1996, Late Quaternary stratigraphy, sealevel history, and paleoclimatology of the southeast Florida outer continental shelf [Ph.D. thesis]: St. Petersburg, University of South Florida, 280 p.

Toscano, M.A., and Lundberg, J., 1997, Late Stage 5 coral reefs, southeast Florida shelf: Sea level, high precision dating and assessment of forcing mechanisms, *in* Carew, J.L., ed., Proceedings, Symposium on the Geology of the Bahamas and other Carbonate Regions, 8th: San Salvador, Bahamas, Bahamian Field Station, Ltd., p. 176–189.

Toscano, M.A., and Lundberg, J., 1998, Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin: Geology, v. 26, p. 255–258.

Toscano, M.A., and Lundberg, J., 1999, Submerged late Pleistocene reefs on the tectonically stable S.E. Florida margin: High-precision geochronology, stratigraphy, resolution of substage 5a sea-level elevation, and orbital forcing: Quaternary Science Reviews, v. 18, p. 753–767.

Turmel, R.J., and Swanson, R.G., 1976, The development of Rodriguez Bank, a Holocene mudbank in the Florida reef tract: Journal of Sedimentary Petrology, v. 46, p. 497–518.

Wanless, H.R., 1989, The inundation of our coastlines: Past, present and future with a focus on south Florida: Sea Frontiers, v. 35, no. 5, p. 264–271.

Wilkinson, C.R., 1993, Coral reefs of the world are facing widespread devastation: Can we prevent this through sustainable management practices? Proceedings, International Coral Reef Symposium, 7th, Guam, v. 1, p. 11–21.

Wilson, J.L., 1975, Carbonate facies in geologic history: New York, Springer-Verlag, 471 p.

B

Holocene Sediment Thickness along the Florida Reef Tract

The Everglades

Gulf of Mexico

Florida Bay

inner shelf
outer shelf
The Elbow Reef
sinkhole
Captain Roy's Reef
Grecian Rocks
White Bank
French Reef
Molasses Reef
Conch Reef

Upper Keys
Key Largo
Windley Key
Middle Keys
Alligator Reef
Lower Keys
Tennessee Reef
upper-slope terrace
3-4 m thick

New Ground Shoal
Ellis Rock
Marquesas-Quicksands Ridge
Rebecca Shoal
Marquesas Keys
Boca Grande Channel
Key West
Halfmoon Shoal
Hawk Channel
Sombrero Key Reef
Straits of Florida
shelf margin
upper-slope terrace
paleoshorelines
sediment wedge
Looe Key Reef
Sand Key Reef
Pelican Shoal

N

Measured in Meters

Land	4 - 5
Paleoshorelines	5 - 6
Buried reef flats	6 - 7
Outlier reefs	7 - 8
0.0 - 0.5	8 - 9
0.5 - 1.0	9 - 10
1.0 - 1.5	10 - 20
1.5 - 2.0	20 - 30
2 - 3	30 - 40
3 - 4	>40

Miles
Scale = 1:65000
0   5   10   15   20

A

Pleistocene Bedrock Surface along the Florida Reef Tract

The Everglades

Gulf of Mexico

Florida Bay

shelf margin
sinkhole
Captain Roy's Reef
Grecian Rocks
French Reef
Molasses Reef
Conch Reef
oval outlier reef
Alligator Reef

Upper Keys
Key Largo
Lower Matecumbe Key
Channel Two
Channel Five
Long Key
Duck Key
Middle Keys
6-8
8-10
10-12
Tennessee Reef
upper-slope terrace
beginning of upper slope
Coffins Patch
East Washerwoman Shoal
Sombrero Key Reef

New Ground Shoal
Ellis Rock
Marquesas-Quicksands Ridge
Rebecca Shoal
Marquesas Keys
Boca Grande Channel
Boca Grande Key
Key West
Halfmoon Shoal
12-14
10-12
8-10
6-8
4-6
2-4
0-2
14-16
16-18
18-20
20-22
22-24
24-26
30-40
shelf margin
upper-slope terrace
paleoshorelines
primary outlier reef
Sand Key Reef
Pelican Shoal
Looe Key Reef
Big Pine Shoal
6-8
8-10
10-12
12-14
14-18
18-30
30-40
40-70
70-80
80-90
90-100
100-140
140-180
180-220
Big Spanish Channel
Bahia Honda Channel
Moser Channel
Hawk Channel
Straits of Florida
Lower Keys

N

Measured in Meters

Land	24 - 26
Paleoshorelines	26 - 28
Buried reef flats	28 - 30
Outlier reefs	30 - 40
0 - 2	40 - 50
2 - 4	50 - 60
4 - 6	60 - 70
6 - 8	70 - 80
8 - 10	80 - 90
10 - 12	90 - 100
12 - 14	100 - 140
14 - 16	140 - 180
16 - 18	180 - 220
18 - 20	220 - 260
20 - 22	260 - 300
22 - 24	300 - 340

Miles
Scale = 1:65000
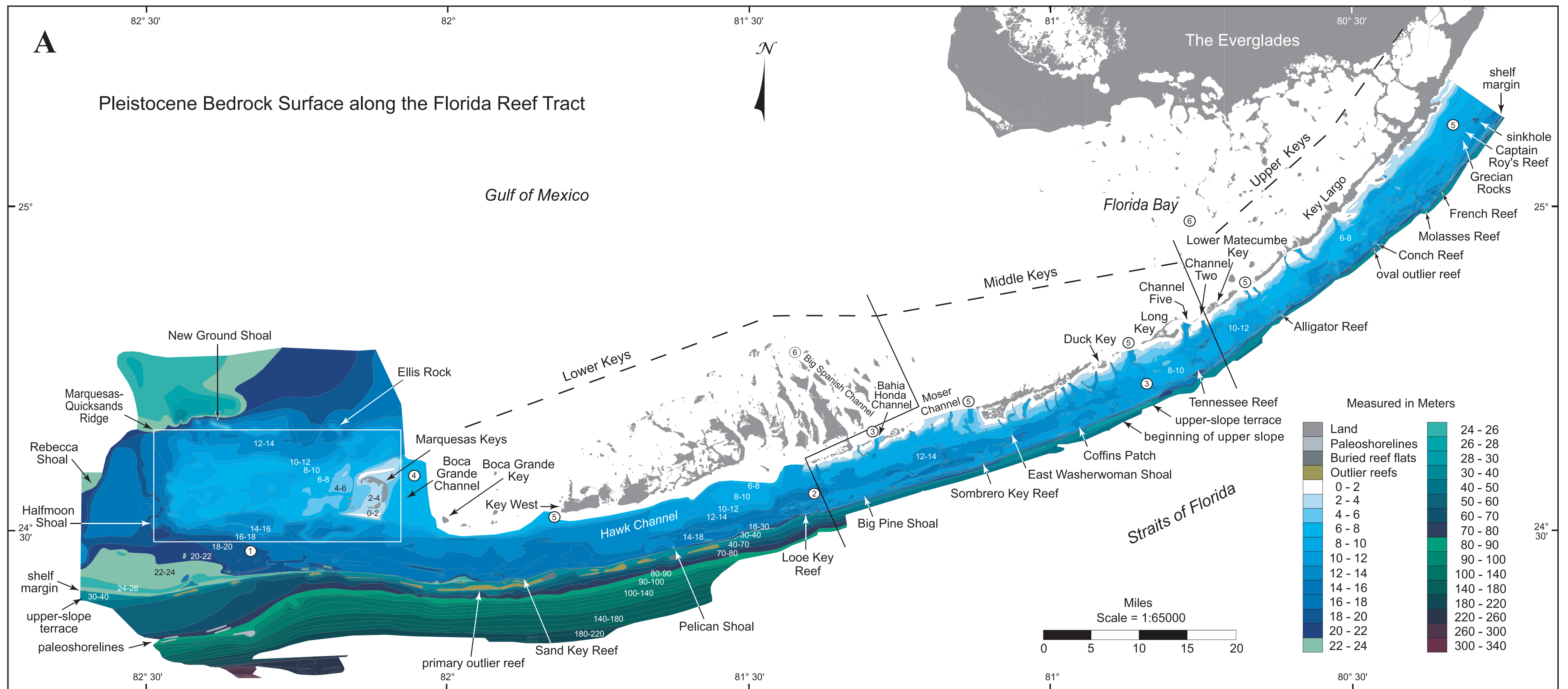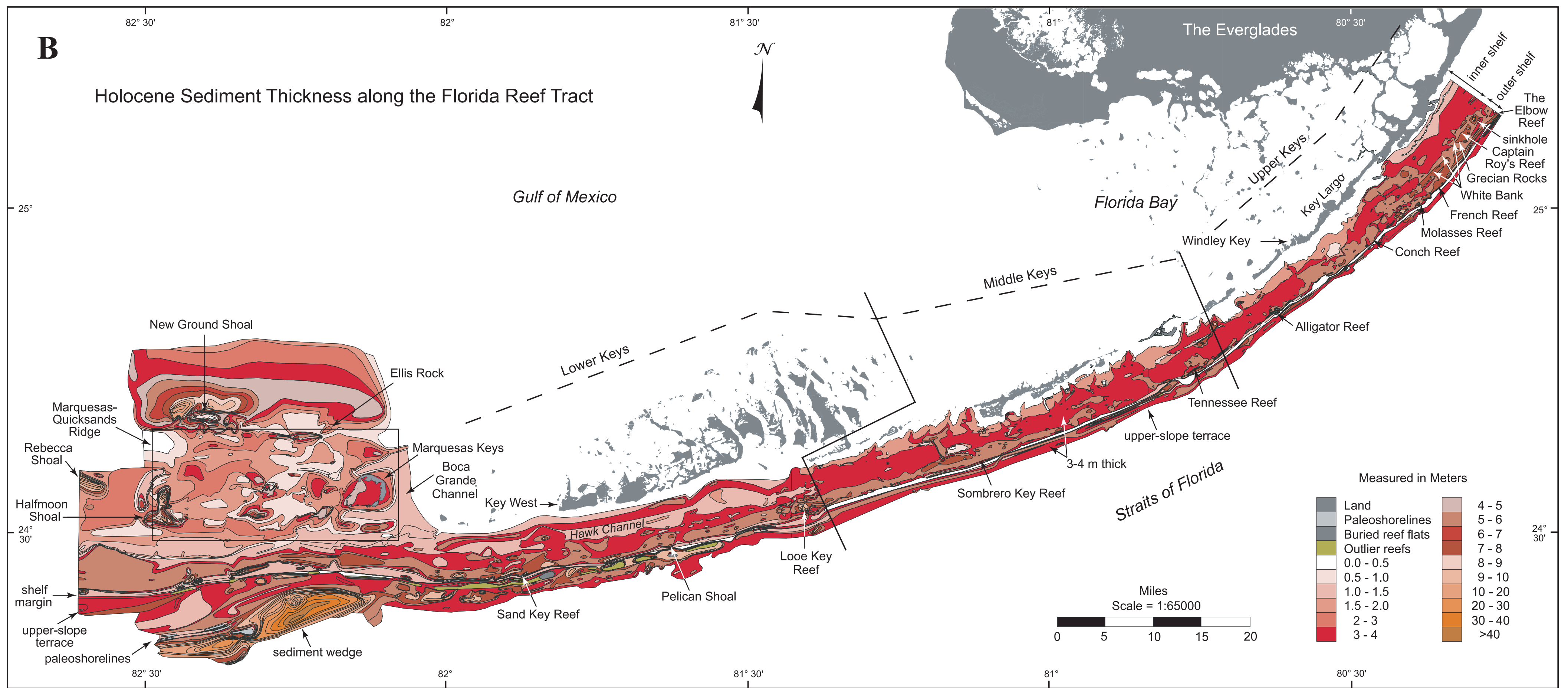0   5   10   15   20

Figure 4. (A) Updated map of regional Pleistocene topography in the Florida Keys area derived from geophysical data. Structure contours and numbers on colors in meters below present sea level. Colors represent different bedrock elevations ranging from highest (pale blues) to lower (darker blues) to lowest (shades of darkest blues and greens). Contacts between colors can be interpreted to represent positions and shapes of Holocene shorelines as sea level rose. Outlier reefs are in shades of brown (light = high relief, dark = low relief or buried). Map scale is too small to show four tracts of outlier reefs. The 80-ka shelf-margin reef coincides with a dark blue line just landward of the outlier reefs. Note elevated ridge in the Gulf of Mexico (large rectangle) on which the Marquesas Keys are located. Also note most extensive areas of palest colors (i.e., shallowest depths mapped) are around the Marquesas Keys and along the inner shelf of the middle and upper Keys. Shelf-wide, bedrock elevations are several meters lower to the southwest than northeast, indicating the shelf flooded from southwest to northeast. Flooding direction is confirmed by radioisotope dates on corals. Circled numbers denote sequential 'stages' in which various areas became submerged during the Holocene: 1 at 18 m below present sea level; 2 at 14 m; 3 at 10 m; 4 at 6 m; 5 at 4 m; and 6 at 2 m (see text for discussion).

(B) Isopach map of Holocene carbonates. Sediment thickness was interpreted from geophysical data and probing with a rod. Reef data based on drill cores. Contours in meters. Colors represent thicknesses ranging from bare bedrock (white) to thinnest (pale pinks) to thicker (dark reds) to thickest (rust). White area at shelf margin denotes seaward sediment-free side of Pleistocene shelf-edge reef. Sediments are generally ~3 to 4 m thick shelf-wide, indicating offshelf transport in the deeper southwestern area. The open-marine environment there is subject to stronger hydrologic processes than the more restricted northeastern marine setting. Note areas of thinnest coverage (pale pinks) generally correspond to areas of highest bedrock elevations. The isopach map shows sites and types of localized sedimentary processes: accumulation in enclosed bedrock lows (north of New Ground Shoal and in sinkhole off Key Largo) and behind rock barriers (east of Halfmoon Shoal), and offshelf transport (sediment wedge southwest of the Marquesas Keys). Deep water around the Marquesas-Quicksands ridge and strong currents in Boca Grande Channel indicate that ridge sands form in place. Both maps show the location of NOAA's newly named Captain Roy's Reef off north Key Largo and the generally margin-parallel nature of Pleistocene and Holocene geomorphic trends seaward of the keys.

Regional Quaternary submarine geomorphology in the Florida Keys
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Figure 4
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